Simulations for Multiple-grid Inertial Electrostatic Confinement (IEC)

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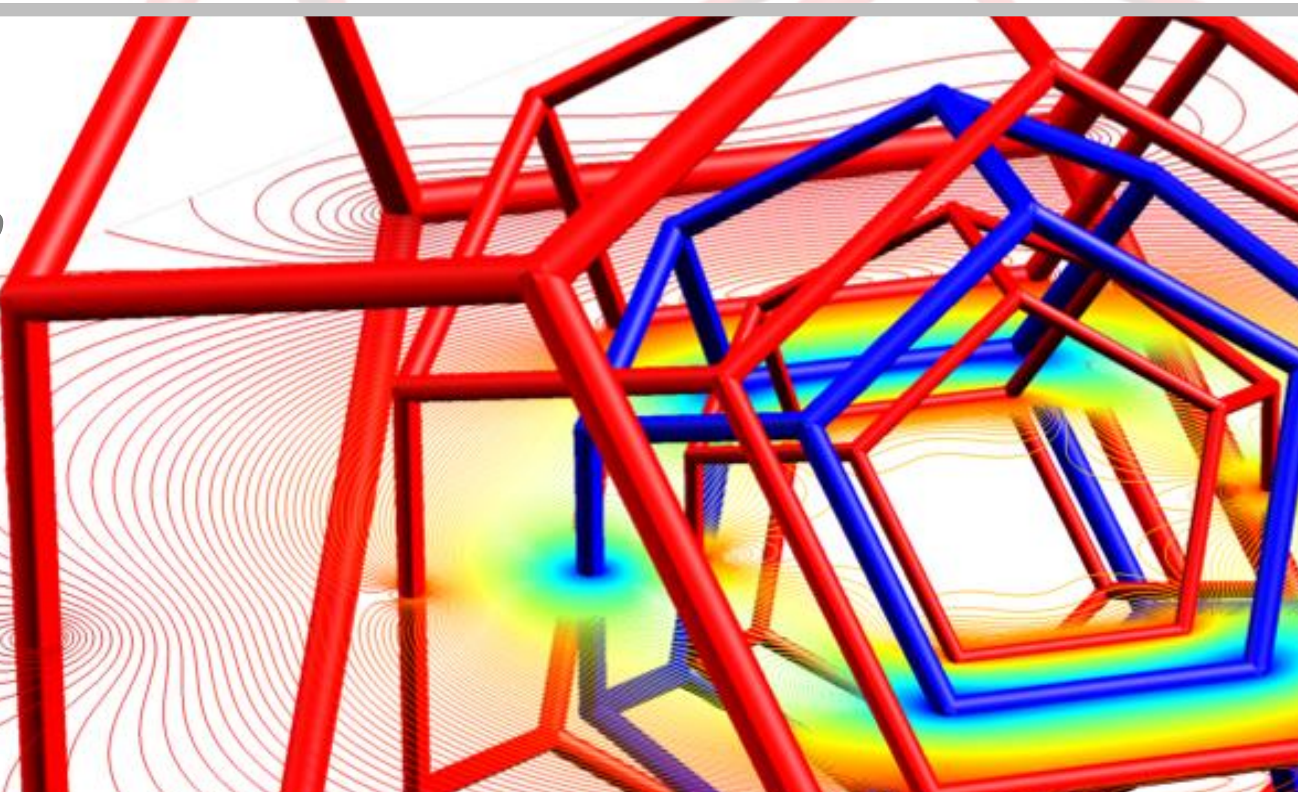
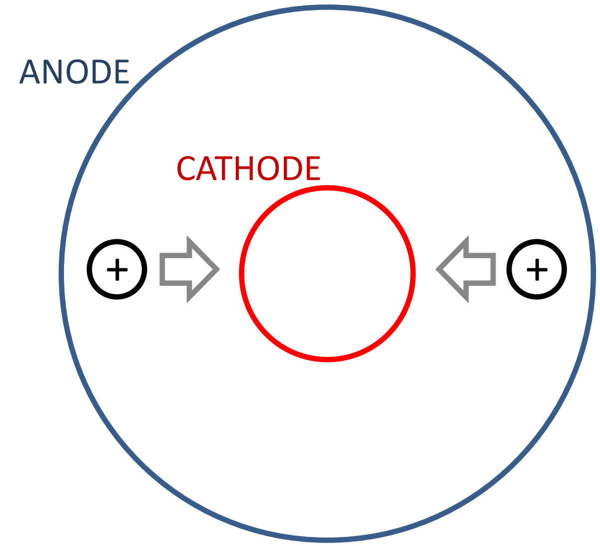
GRANT #NNX13AL44H



20th Advanced Space Propulsion Workshop
Ohio Aerospace Institute
November 17-19, 2014
Cleveland, Ohio

Inertial Electrostatic Confinement (IEC) Fusion - Background



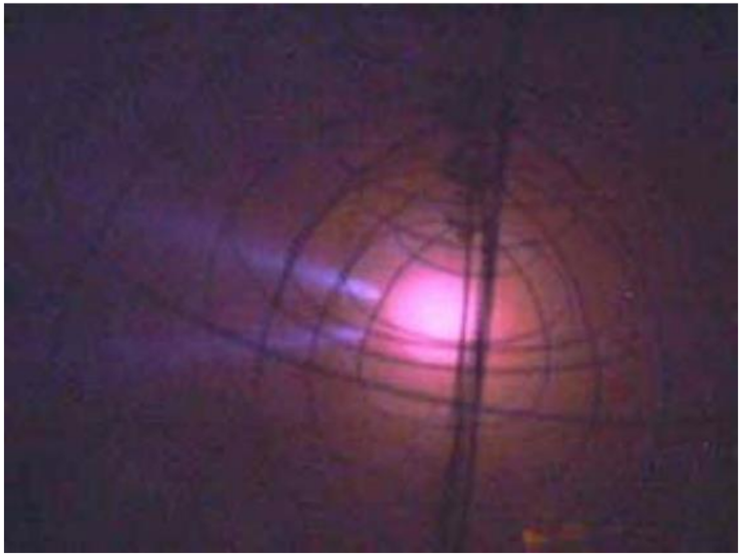
- Two concentric spherical grids create a potential well
- Ions are accelerated towards the center, with each pass through is a chance to fuse

Barriers to net power generation

- Ion losses to grid wires
- Thermalization
- Collisions with background gas
- Bremsstrahlung losses

From: Deitrich et al. "Experimental Verification of Enhanced Confinement in a Multi-grid IEC Device"

Multiple-grid IEC – brief history



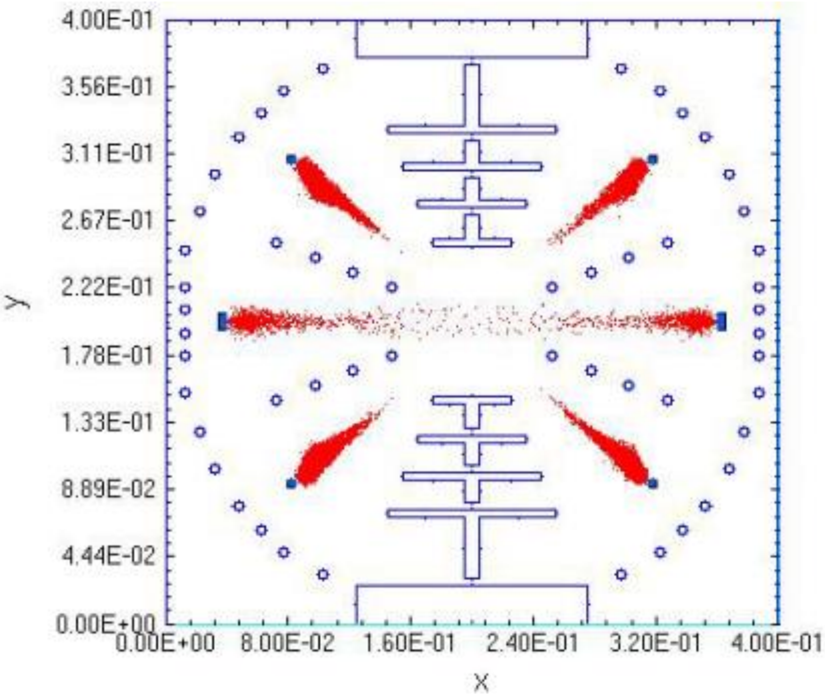
Ray Sedwick et al. used additional grids to focus ion beams.

BENEFITS OF MULTIPLE-GRID IEC OVER TRADITIONAL IEC:

1: **Ion lifetimes extended:** From 10's of passes to 10^3-10^6 passes

2: Greater confinement time
\+ Counter-stream instability
\+ IEC trap kinematics
= Ion bunching

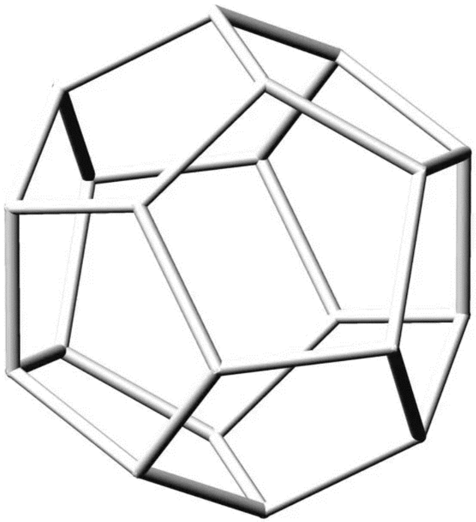
3: **Bunch synchronization → Decreased thermalization**



Multiple-grid IEC – current research

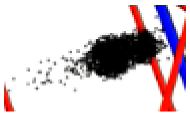
DODECAHEDRAL GRIDS

- **12 Faces → 6 beamlines**
- Highly symmetric
- Another possibility: **Truncated Icosahedron** (Soccer Ball)
- Feed-throughs?



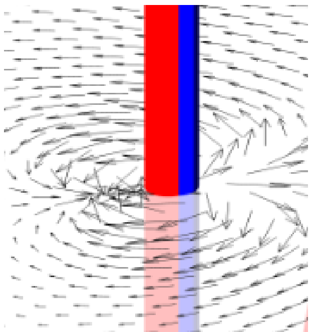
ION BUNCHING

- Potential well can be shaped to encourage ion bunch cohesion

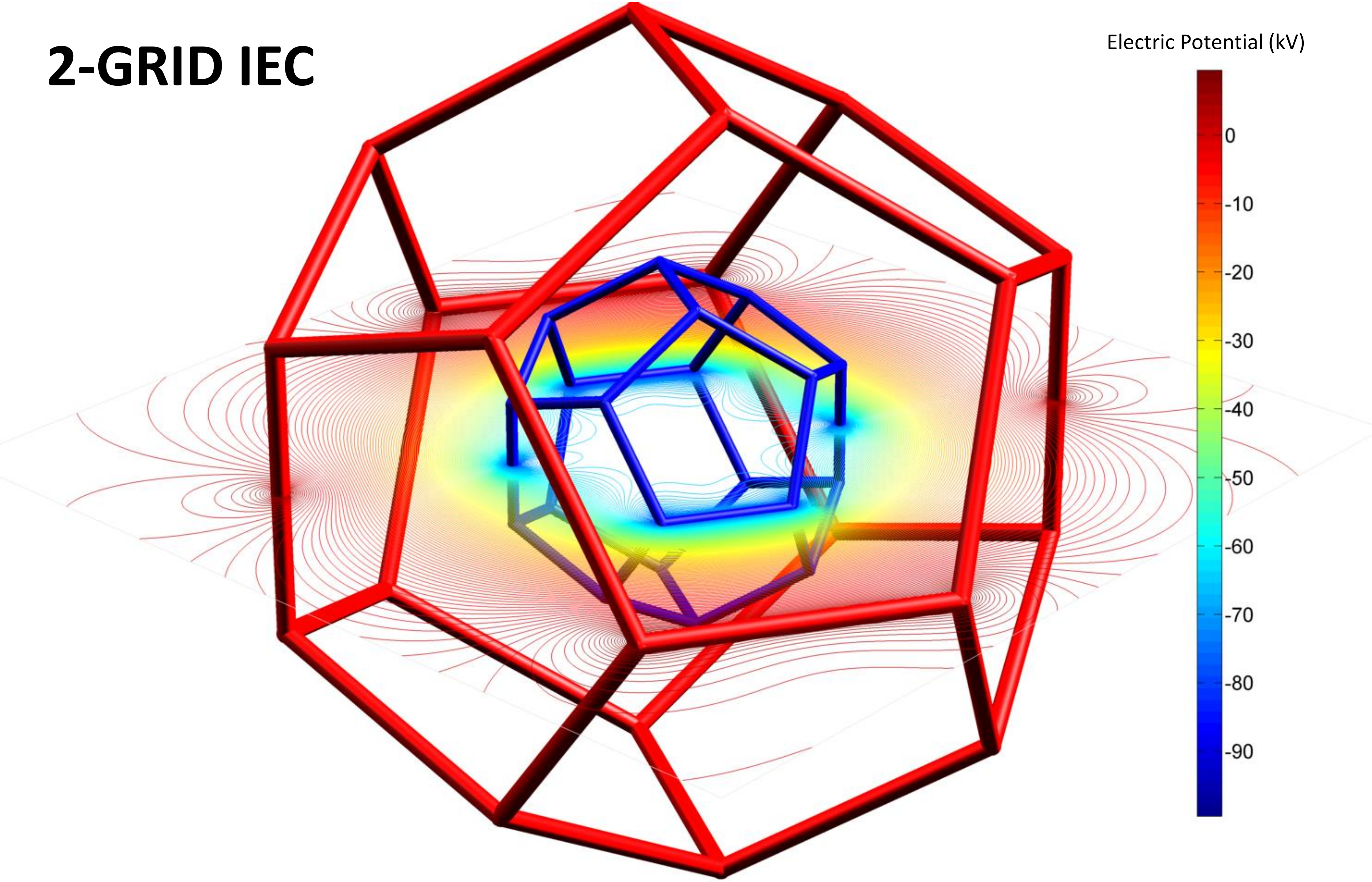


MAGNETIC CORE

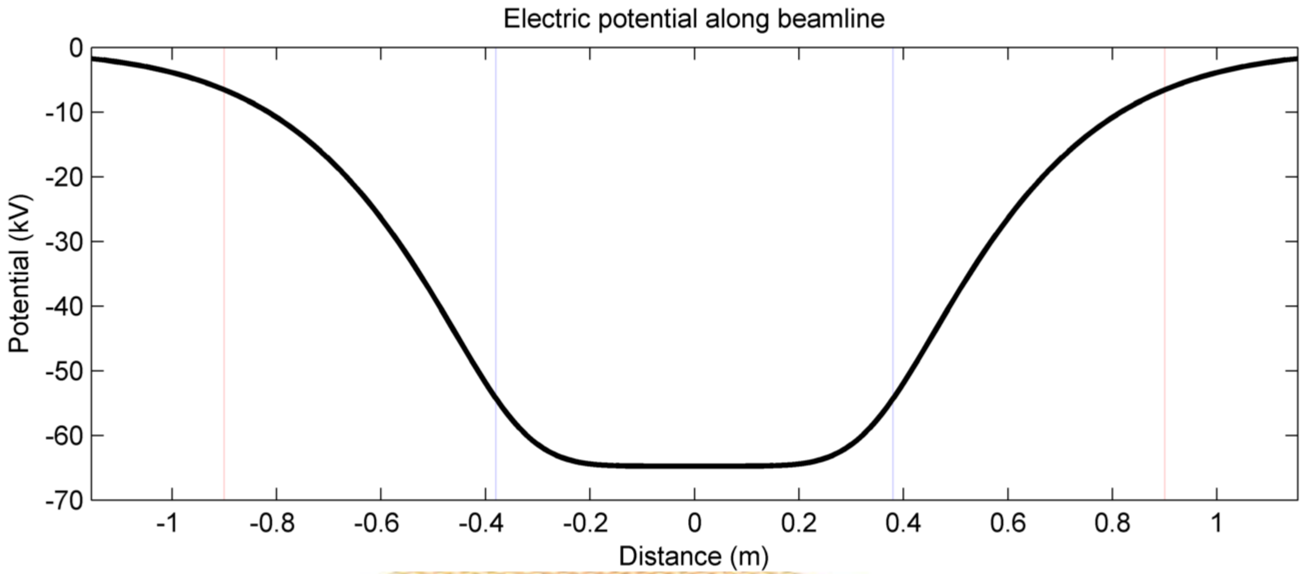
- Confinement of electrons in the core

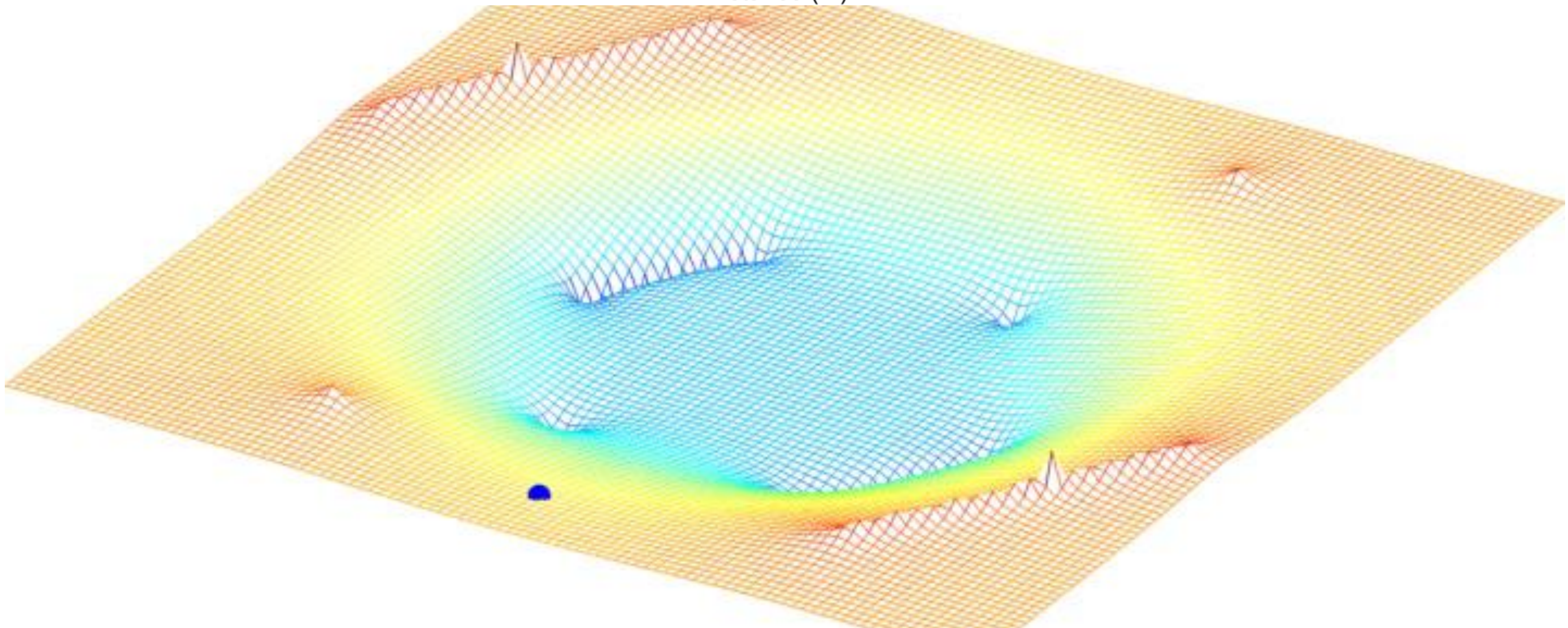


2-GRID IEC

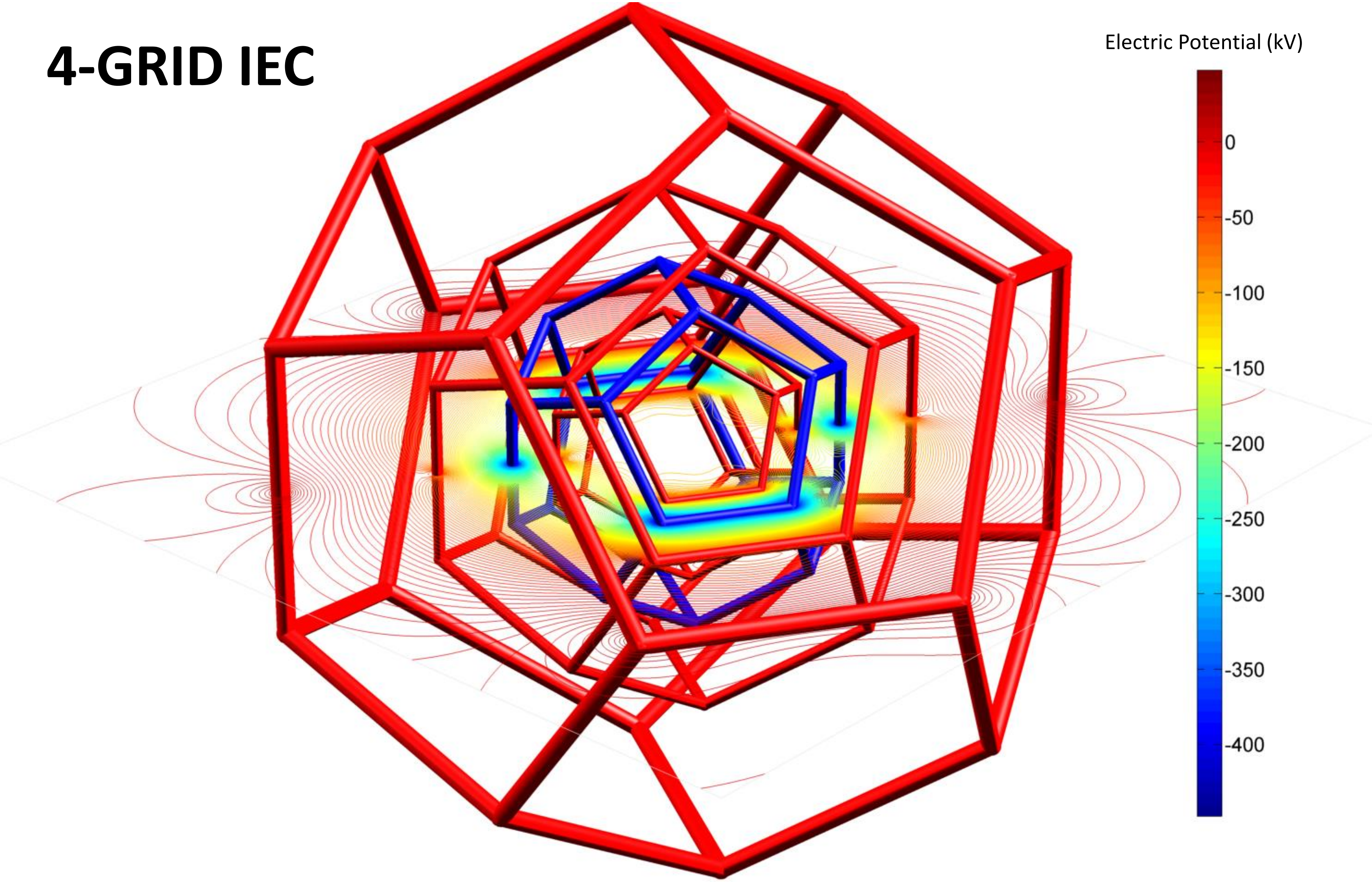


2-GRID IEC

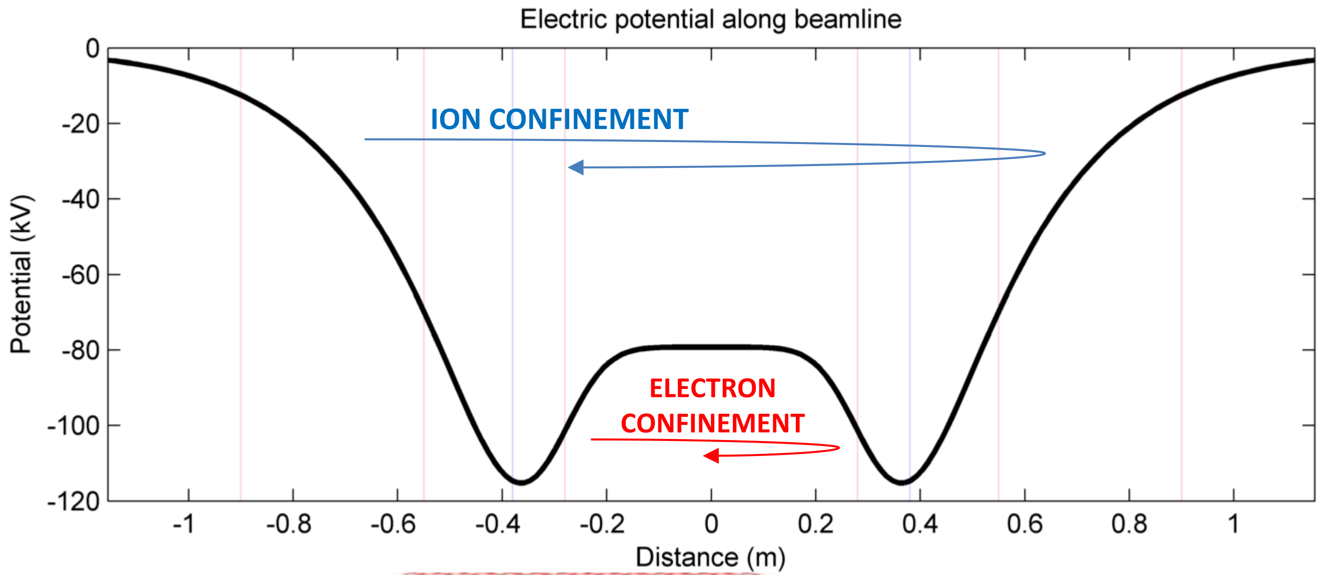

Electric potential along beamline
Potential (kV)
0
-10
-20
-30
-40
-50
-60
-70
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Distance (m)

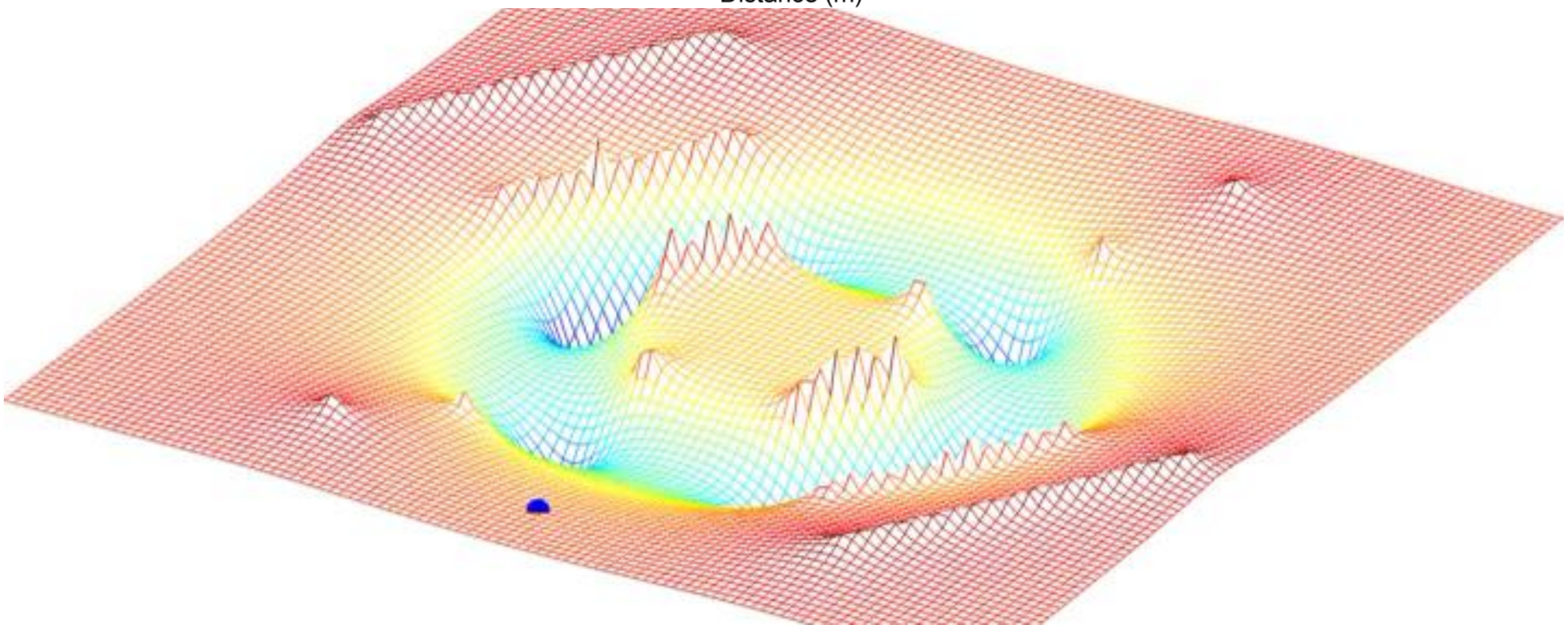


4-GRID IEC



4-GRID IEC


Electric potential along beamline
0
-20
-40
-60
-80
-100
-120
Potential (kV)
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Distance (m)
ION CONFINEMENT
ELECTRON
CONFINEMENT



Particle-particle Discrete Event Simulation

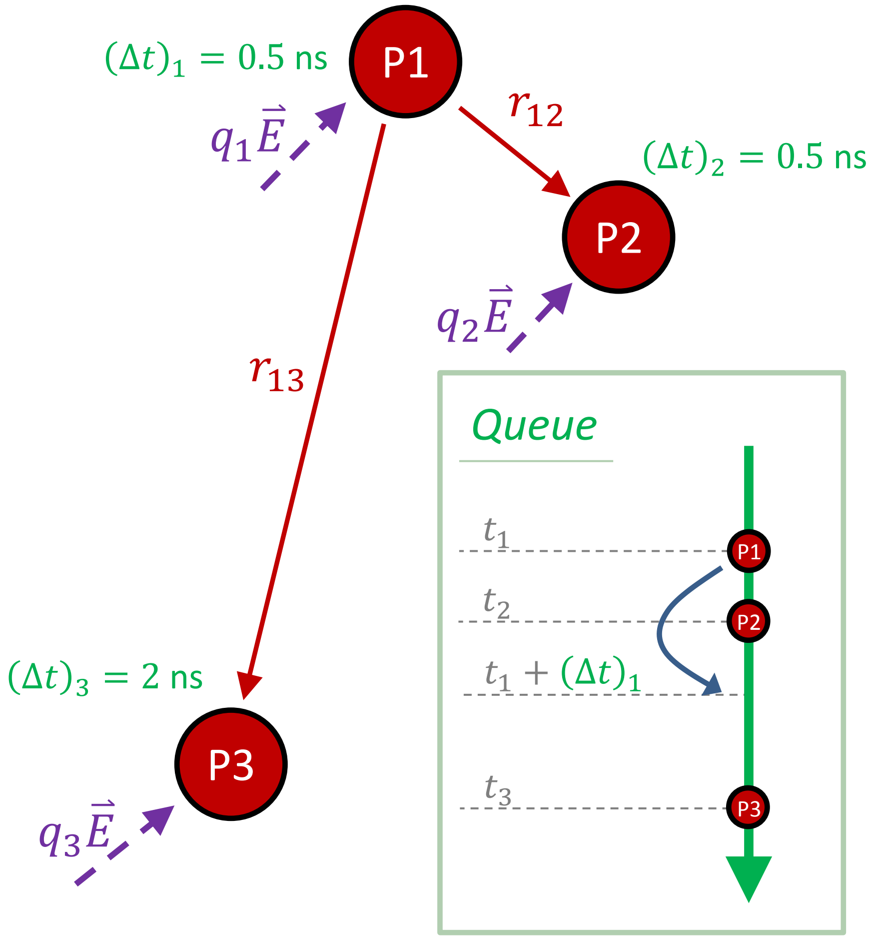
- **Inter-particle forces are calculated directly** (N-body simulation)
  - No need to solve Poisson's equation at each time step
- **No global time-step**, each particle is assigned its own time-step depending on its velocity and acceleration
  - Coulomb collisions are modeled directly by decreasing the time-step values of colliding particles.

$$\Delta t = \sqrt{\eta \frac{a\ddot{a} + k^2}{k\dot{k} + \ddot{a}^2}} \qquad a = \frac{\partial^2 x}{\partial t^2} \qquad k = \frac{\partial^3 x}{\partial t^3}$$

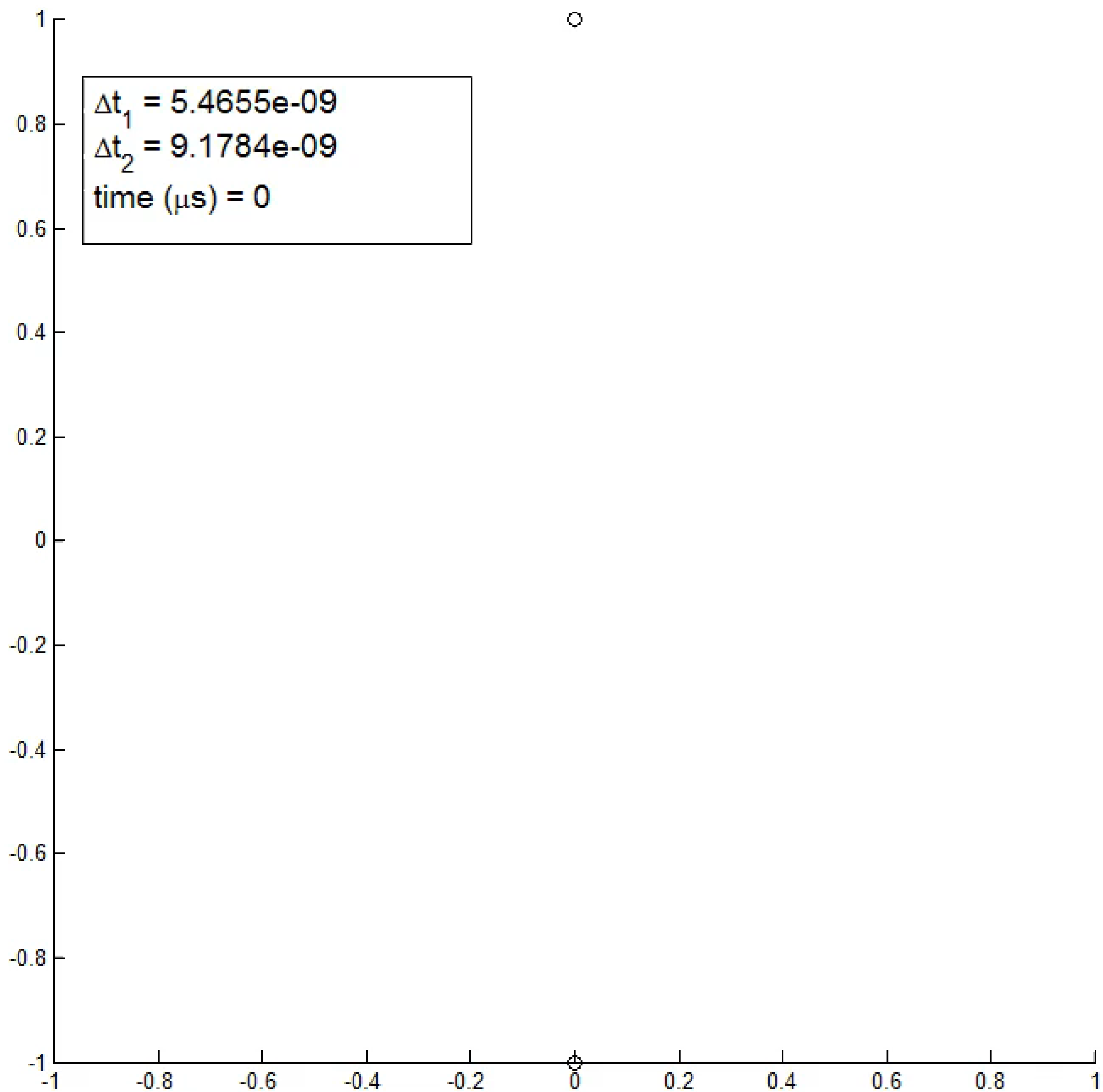
From: *Makino, Aarseth, "On a Hermite Integrator with Ahmad-Cohen Scheme for Gravitational Many-Body Problems" 1992*

- Static E&M fields are calculated once at the beginning of the simulation

$$\vec{a}_i = -\frac{1}{4\pi\epsilon_0}\frac{q_i}{m_i}\sum_{j\neq i}\frac{q_j}{r_{ij}^3}\vec{r}_{ij} + \frac{q_i}{m_i}(\vec{E} + \vec{v}\times\vec{B})$$



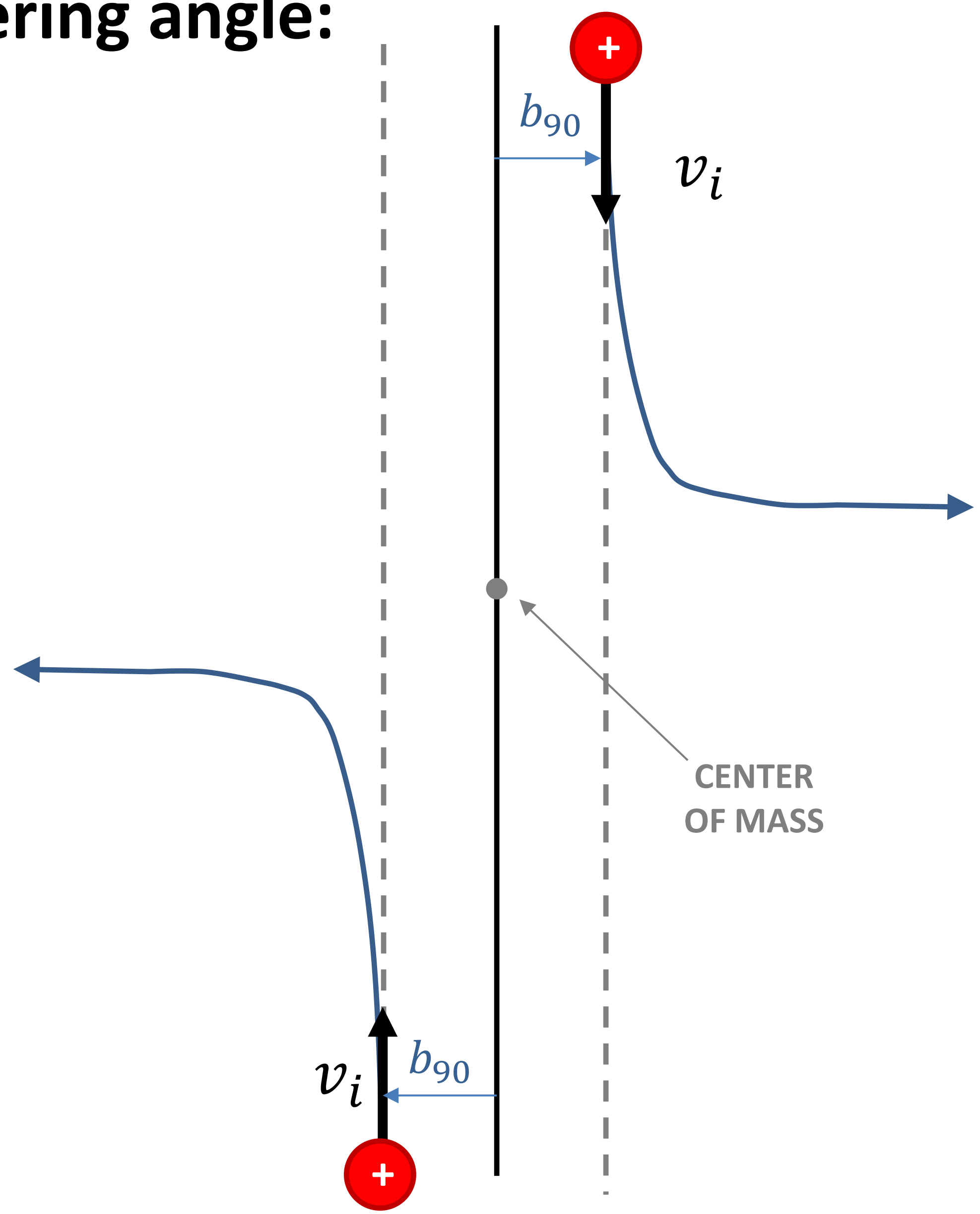
High-angle scatter example



Testing with a known scattering angle:

Equal mass
Equal charge
Equal and opposite velocities

$$b_{90^\circ} = \frac{e^2}{16\pi\epsilon_0 m v_i^2}$$

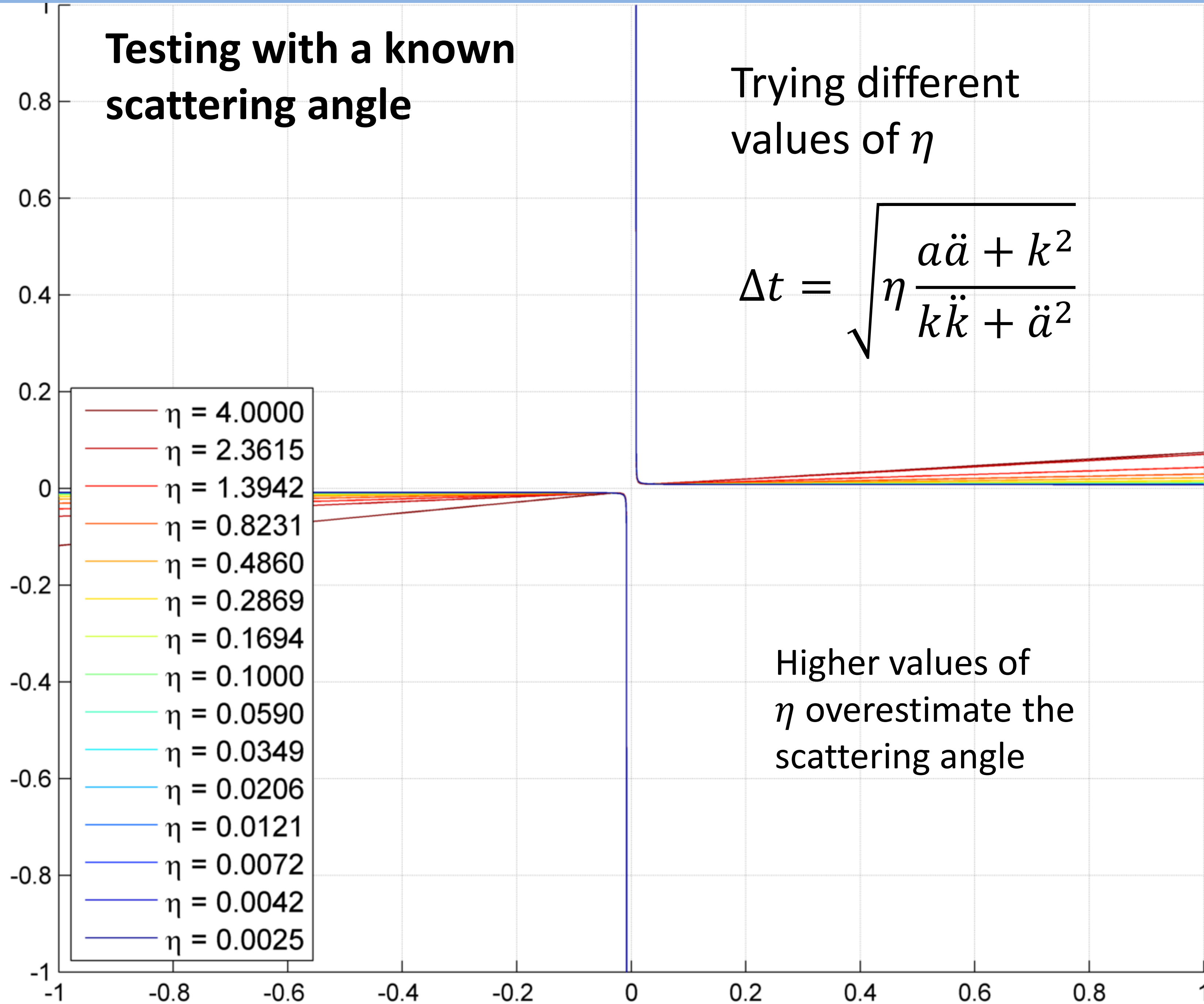


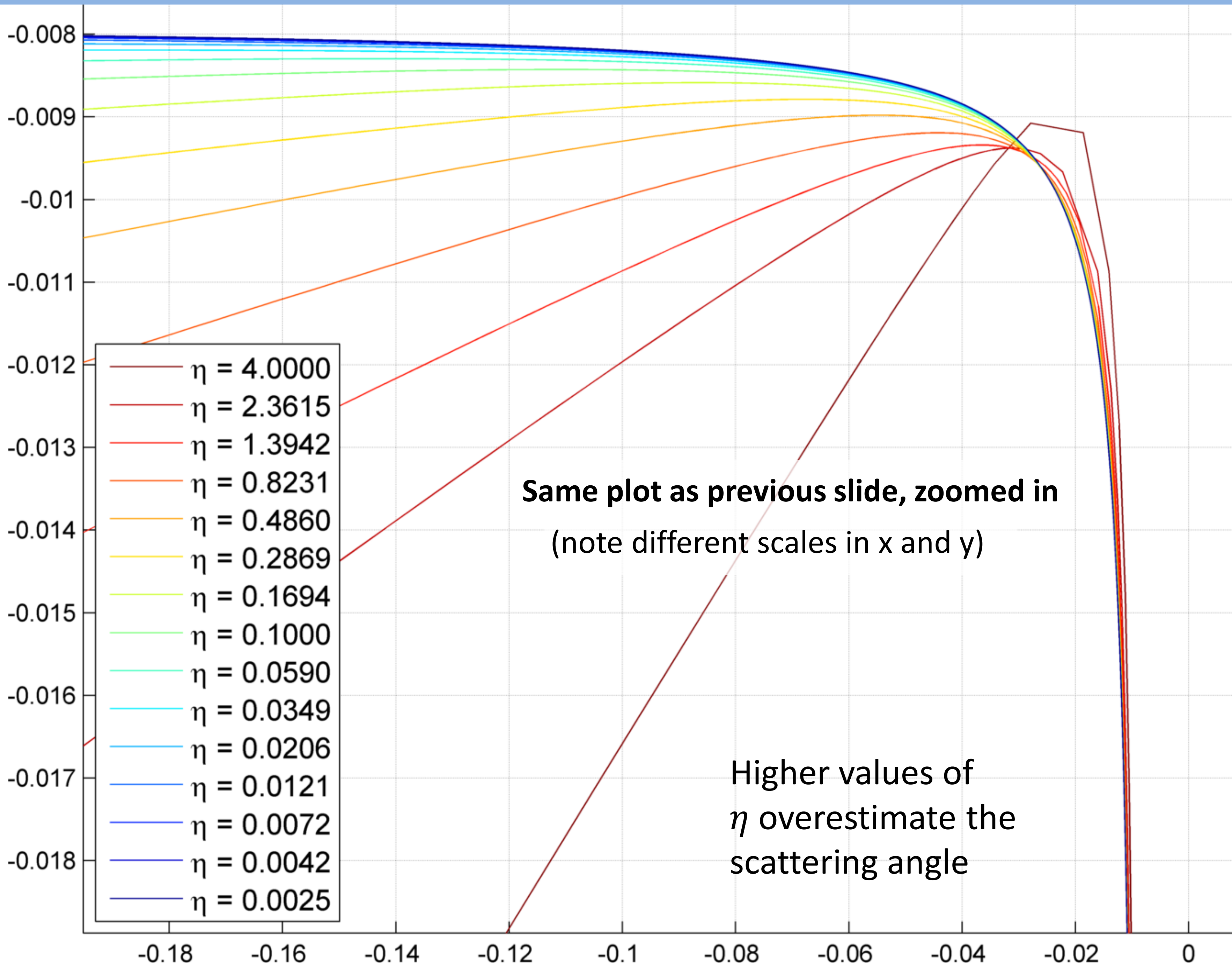
Testing with a known scattering angle

Trying different values of η

$$\Delta t = \sqrt{\eta \frac{a\ddot{a} + k^2}{k\ddot{k} + \ddot{a}^2}}$$

Higher values of η overestimate the scattering angle



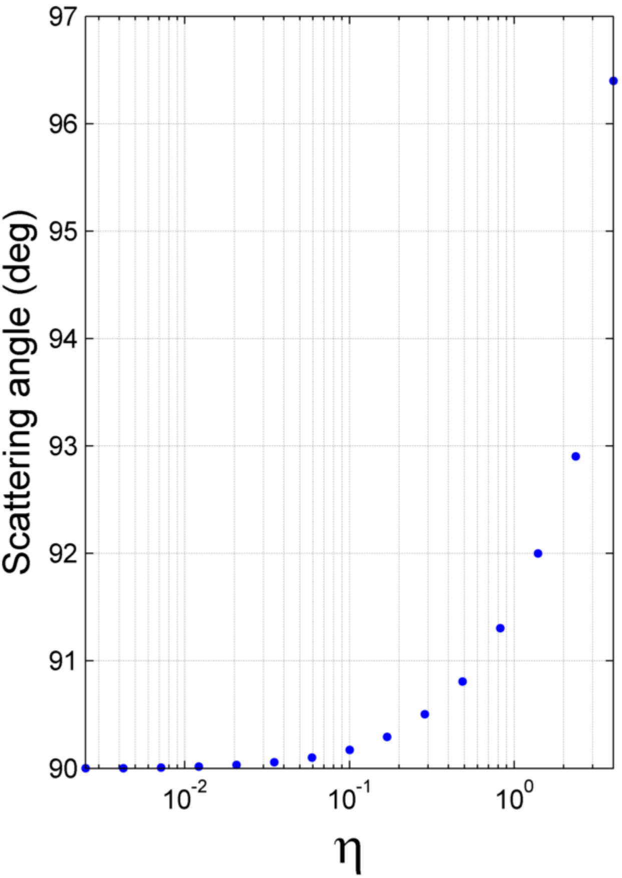


Same plot as previous slide, zoomed in

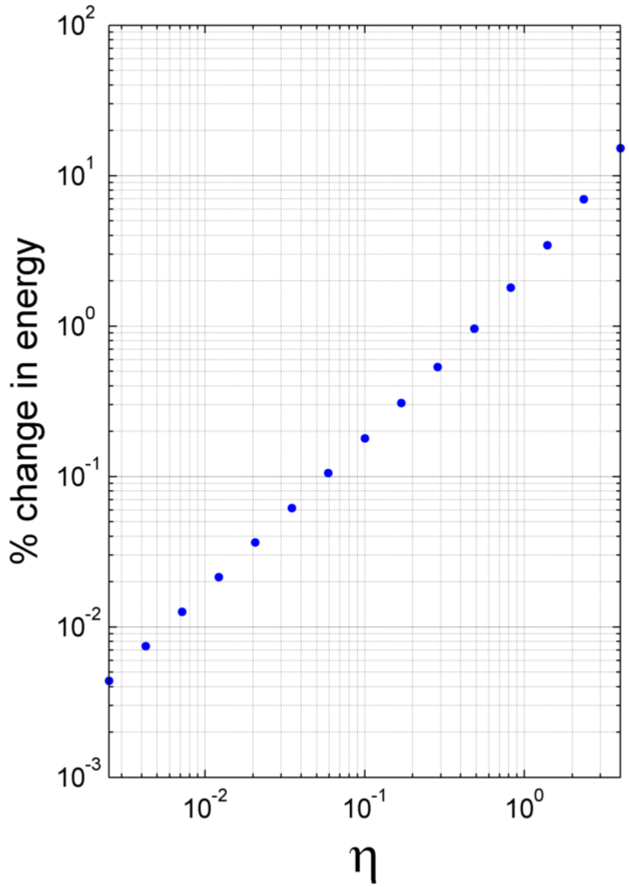
(note different scales in x and y)

Higher values of η overestimate the scattering angle

Solution converges to 90° scatter

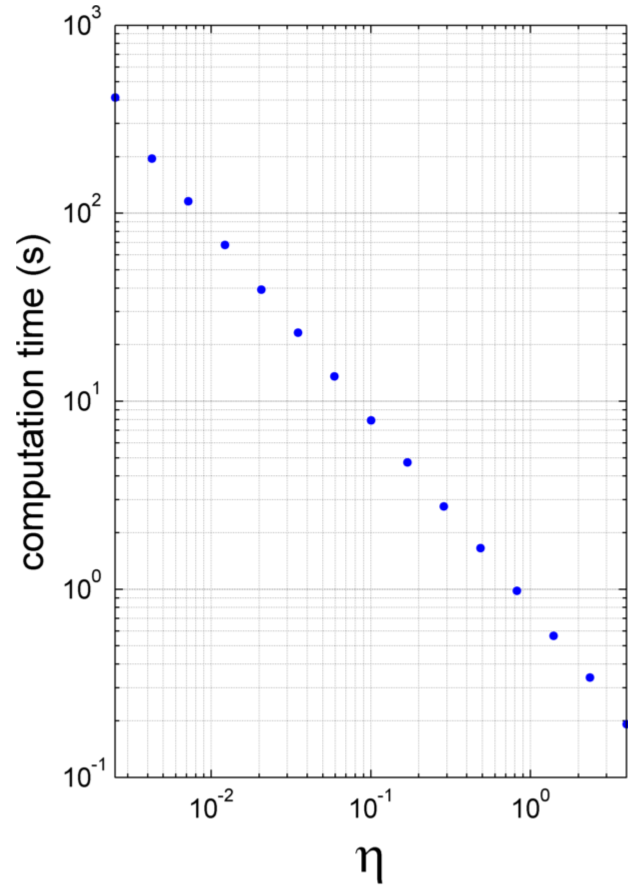


Testing conservation of Energy



$$\%\ \text{change} = 100\frac{|E_\mathrm{f} - E_\mathrm{i}|}{|E_\mathrm{i}|}$$

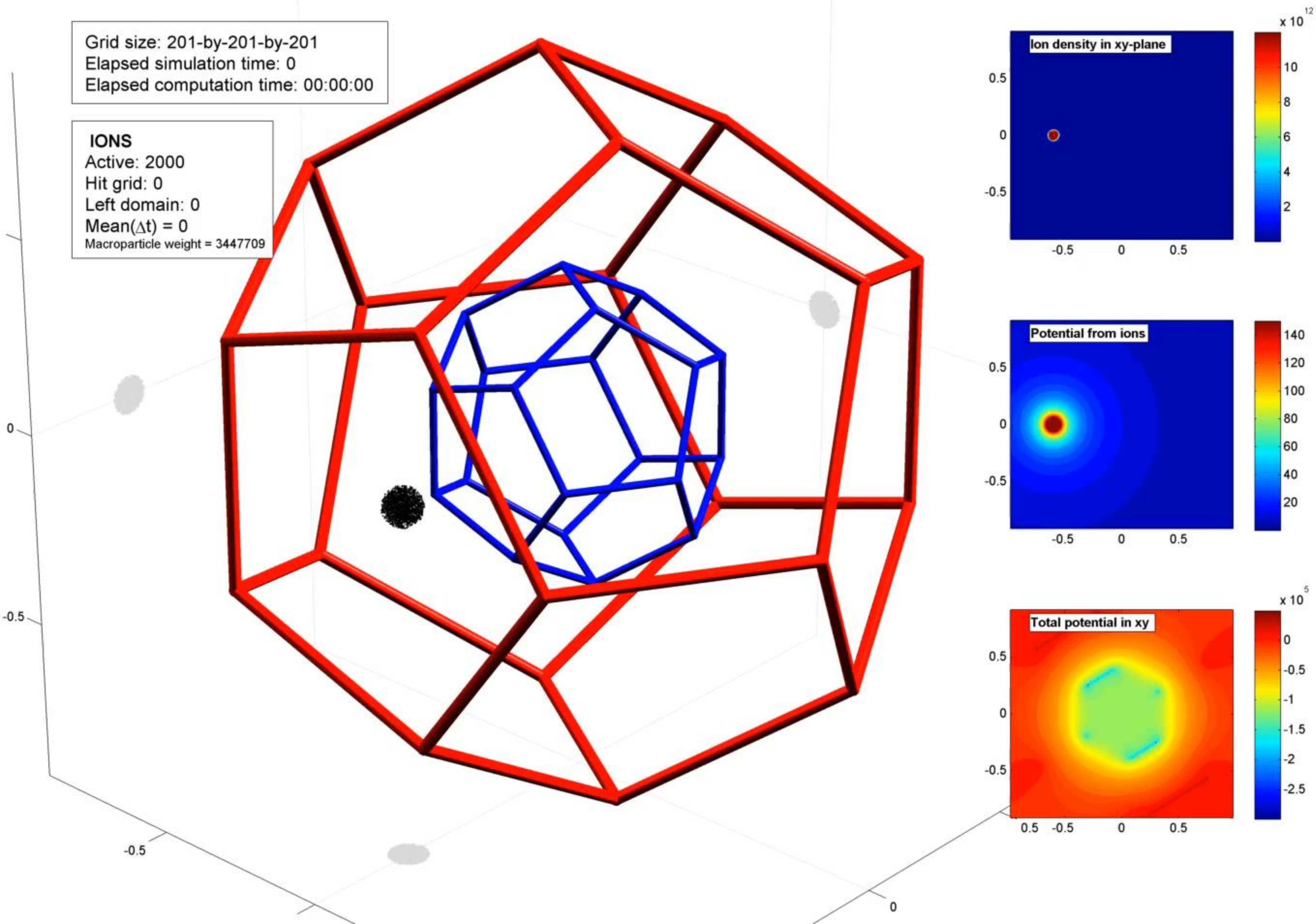
Computation time



Time taken to run the simulation for each η

2-GRID Particle-particle simulation

LOW DENSITY BUNCH

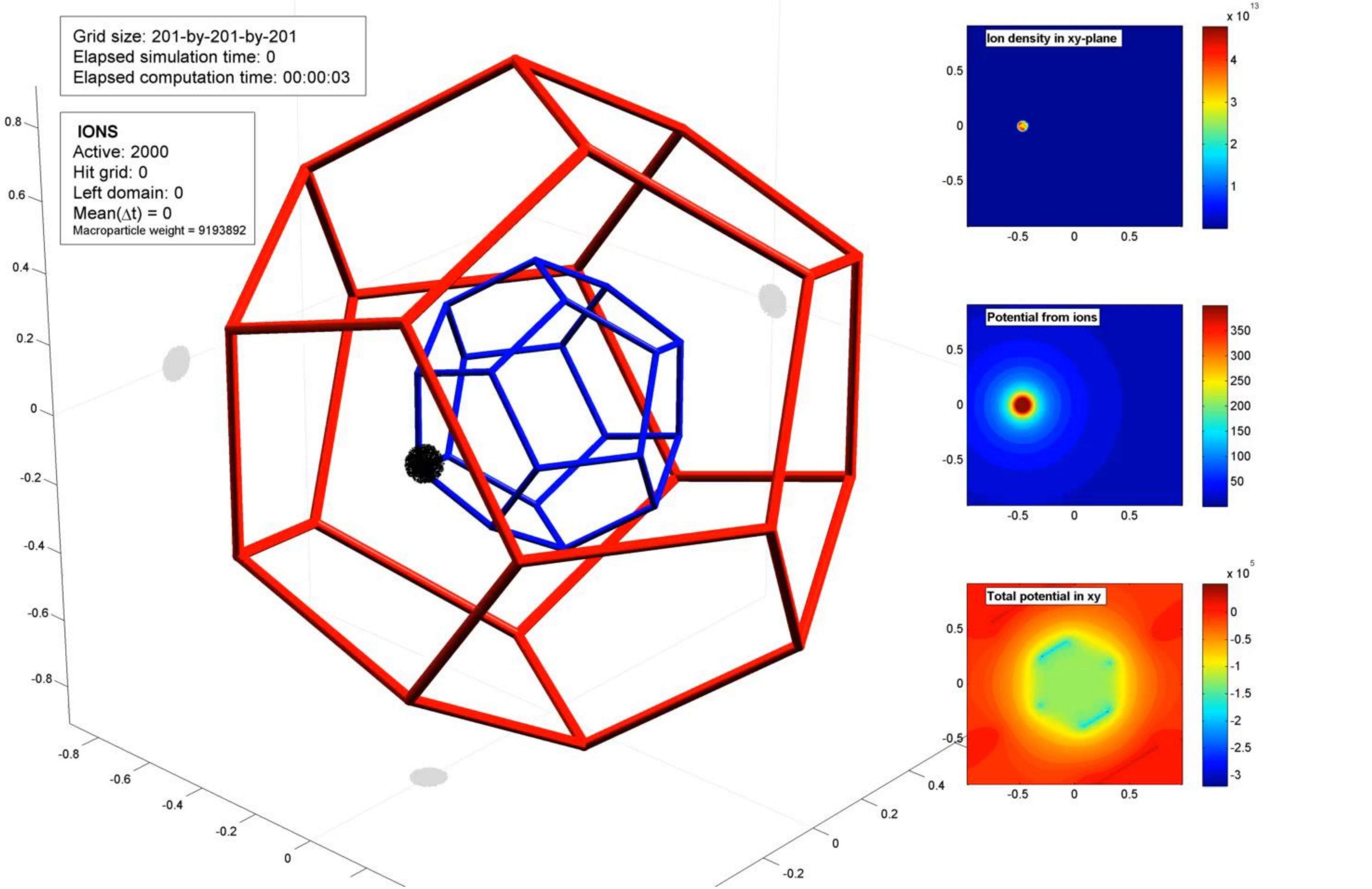


2-GRID Particle-particle simulation

What happens if we increase the density of the ion bunch?

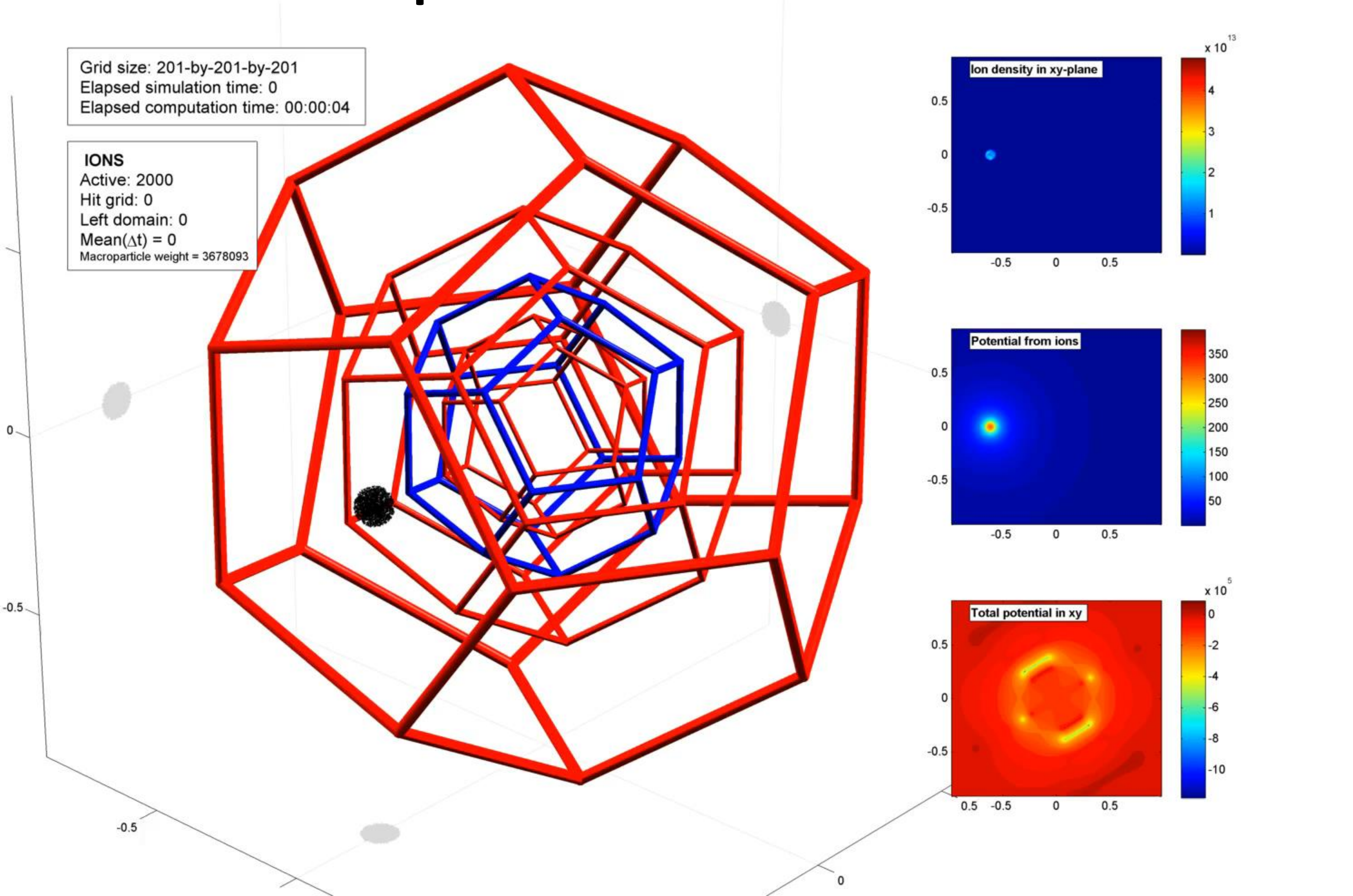
2-GRID Particle-particle simulation

HIGHER DENSITY BUNCH



4-GRID Particle-particle simulation

SAME DENSITY AS PREVIOUS SLIDE



Ion Bunching – The Kinematic Criterion

Ions near the **back** of the bunch are **decelerated** by the Coulomb repulsion from the bunch

Energy **decreases**

Period must also **decrease** to prevent ions from "falling behind"

Kinematic criterion:

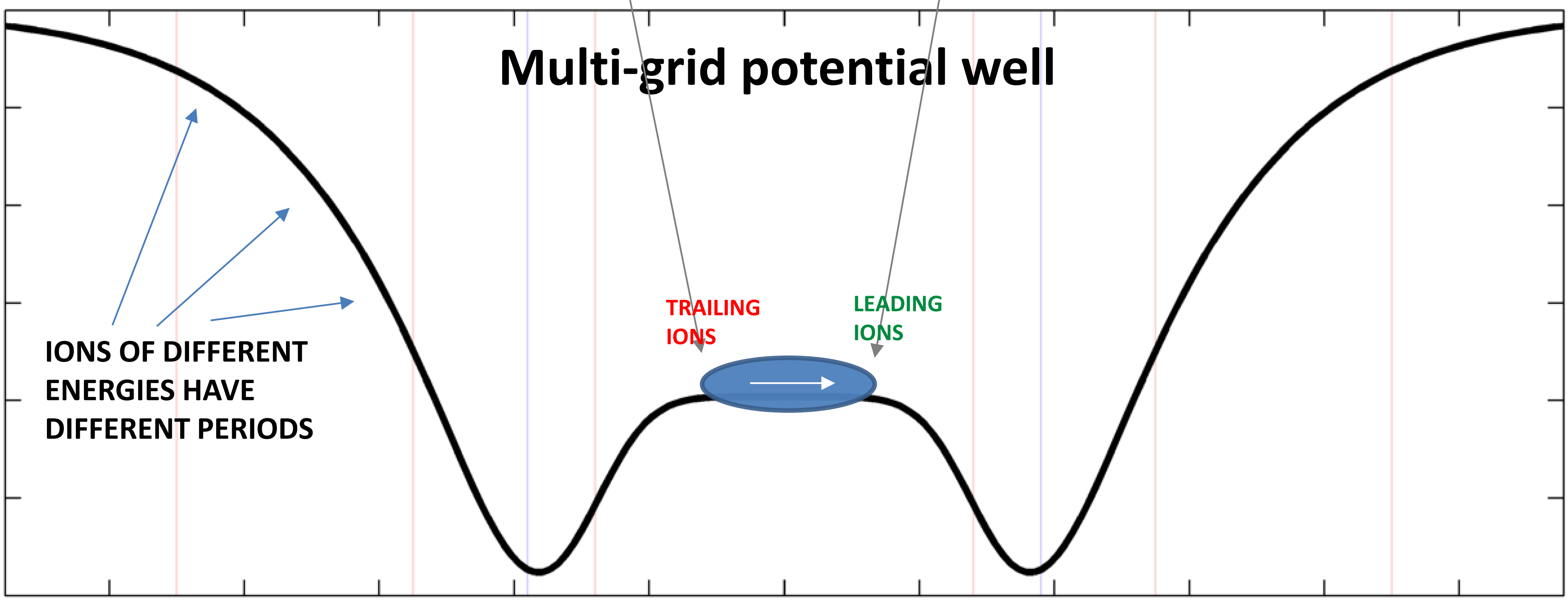
$$\frac{dT}{dE} \geq 0$$

T: Period
E: Ion Energy (KE+PE)

Ions in the **front** of the bunch are **accelerated** by the Coulomb repulsion from the bunch

Energy **increases**

Period must also **increase** to prevent ions from "running away"



Ion Bunching – The Kinematic Criterion

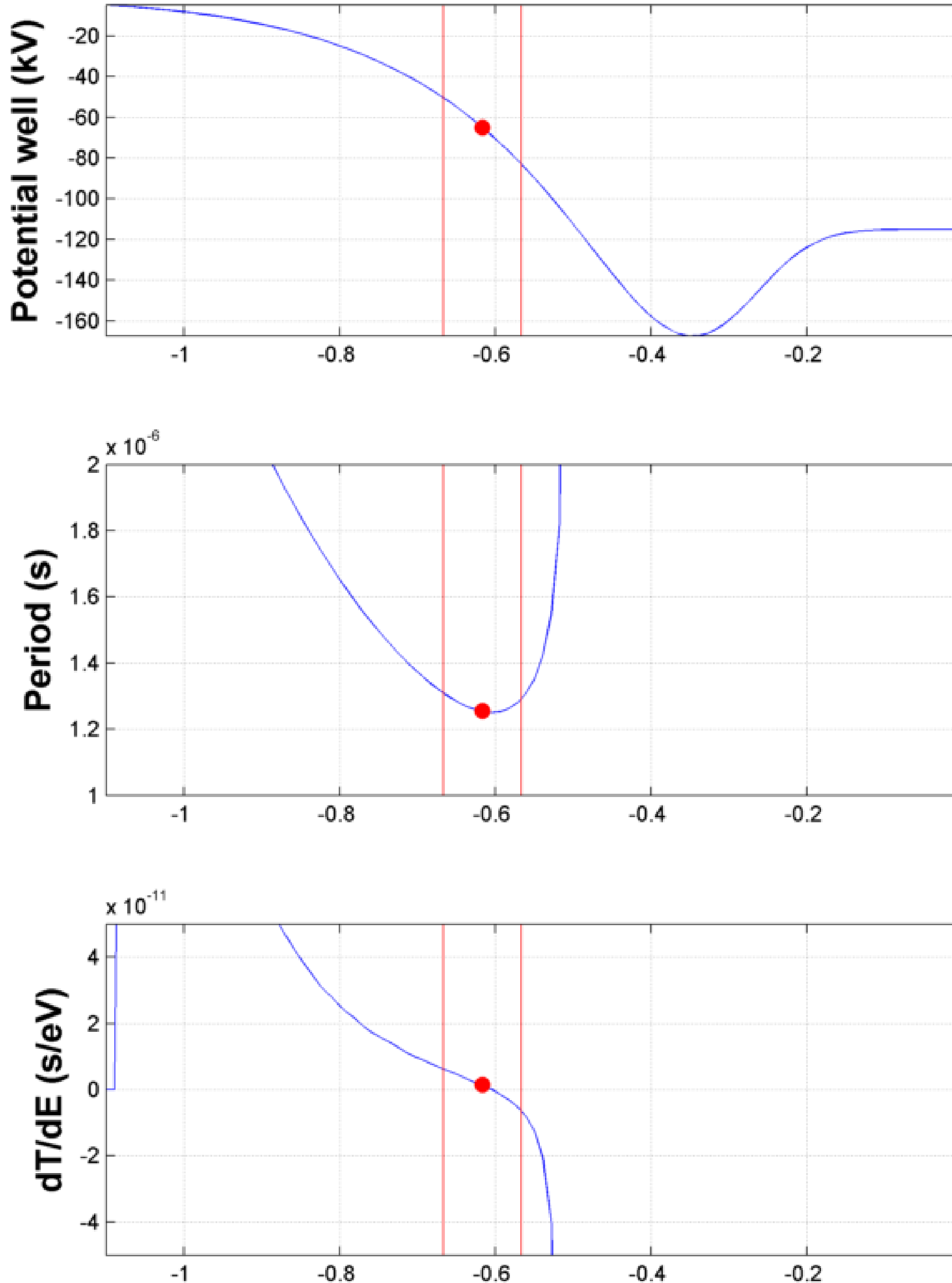
Kinematic criterion: $\frac{dT}{dE} \geq 0$

But $\frac{dT}{dE}$ can't be too large either!

Conditions have to be just right for ions to coalesce into bunches

FUTURE WORK:

"Sculpting" the IEC well to encourage bunch cohesion

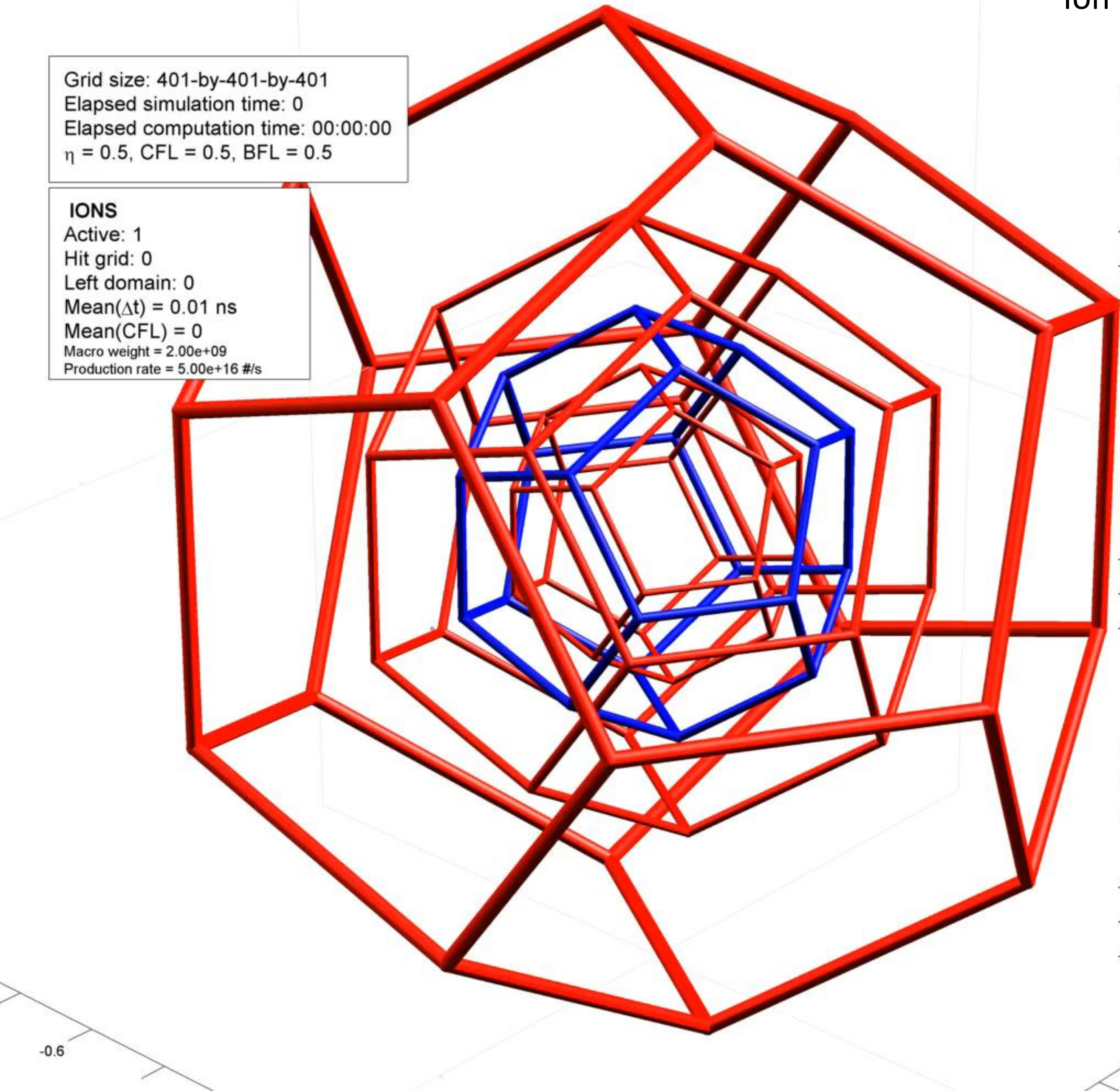


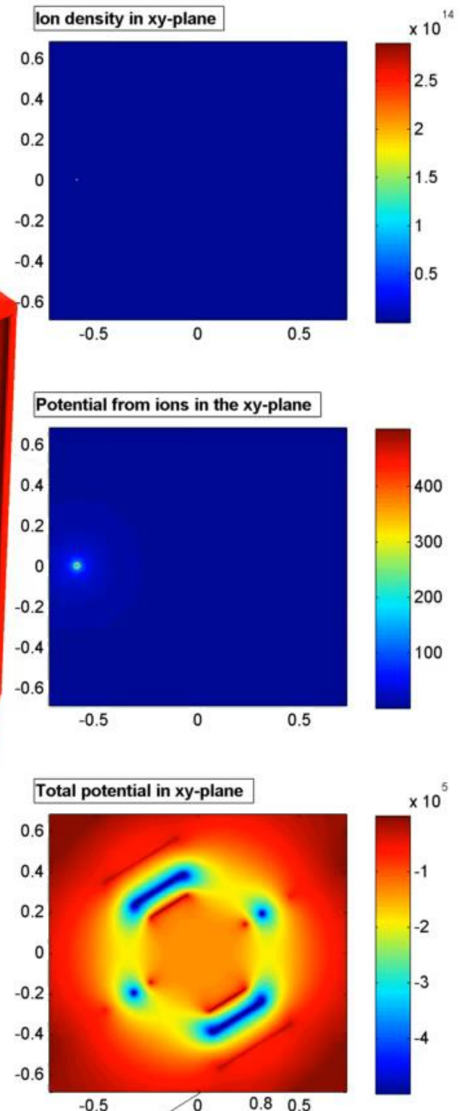
Simulation with constant ion sources

One pass ≈ 0.58 µs

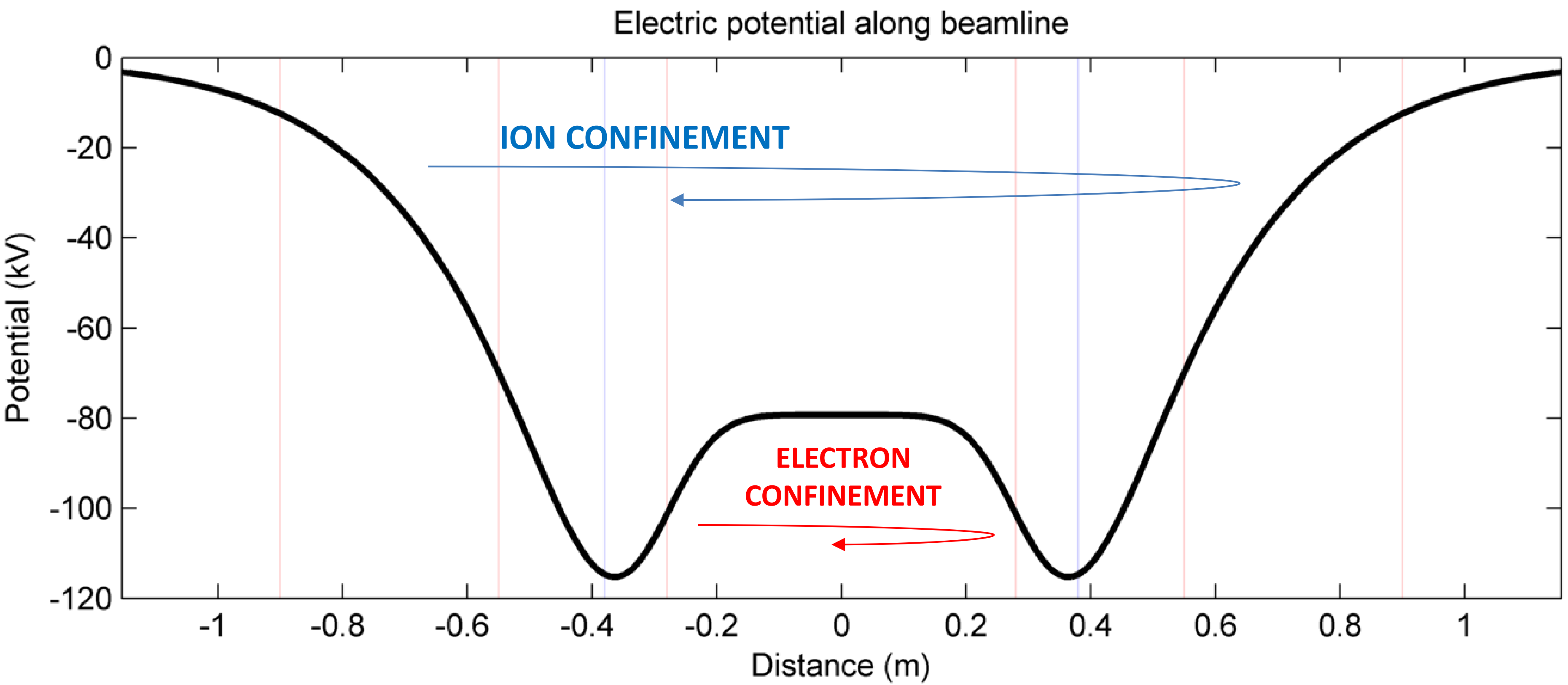
Ion Energy ≈ 50 keV

54 passes simulated





Electron confinement in the IEC core



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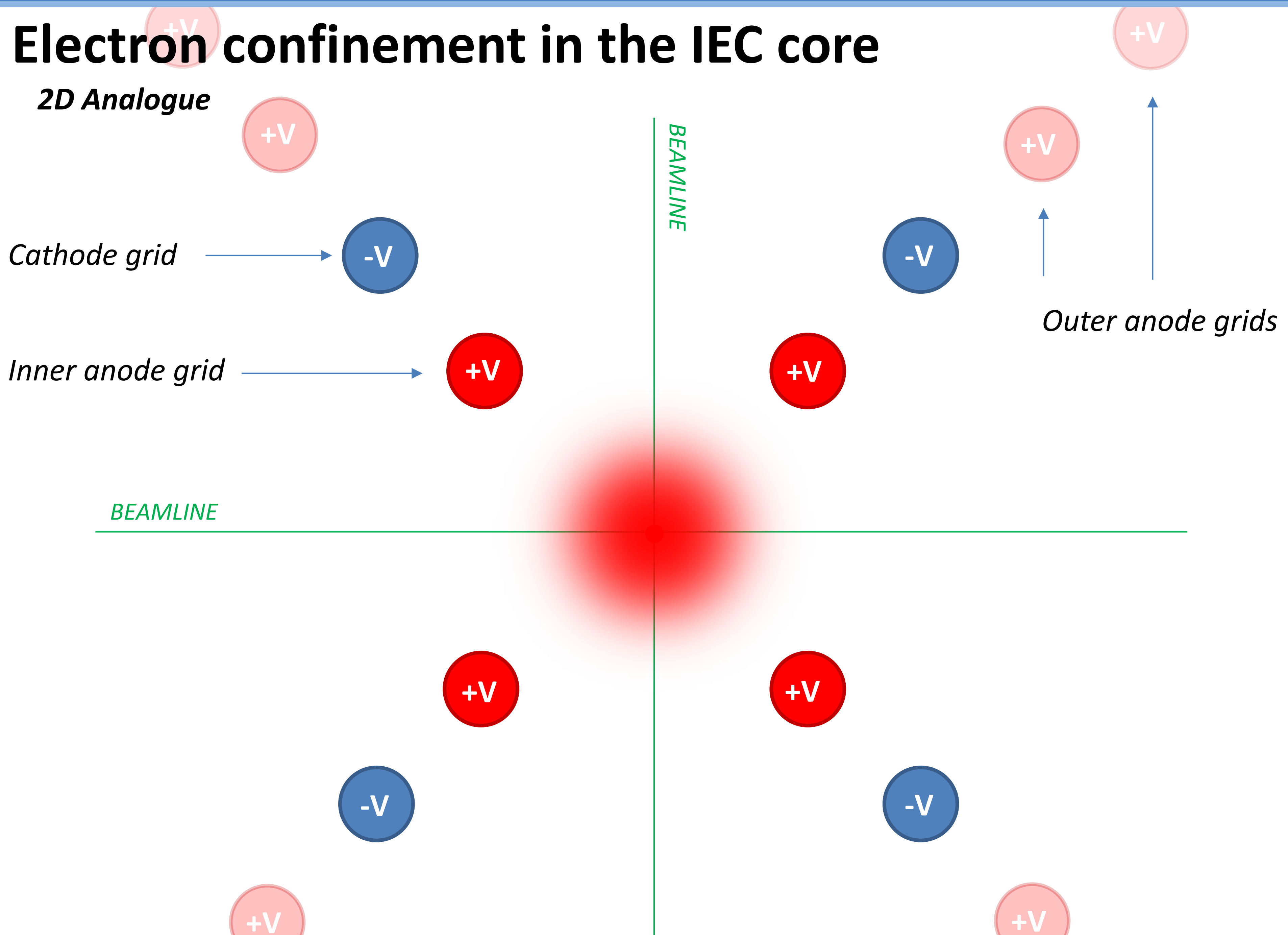
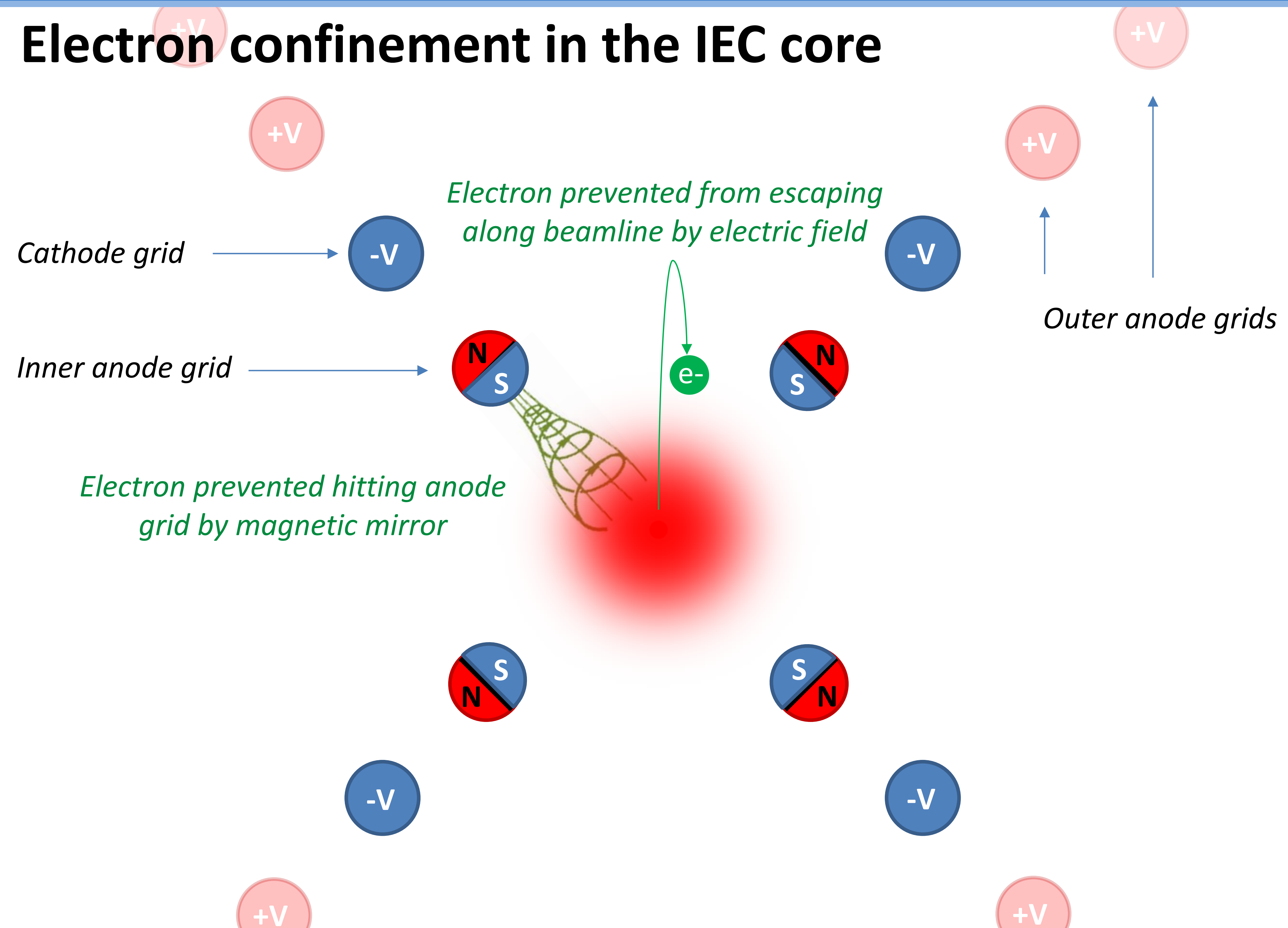
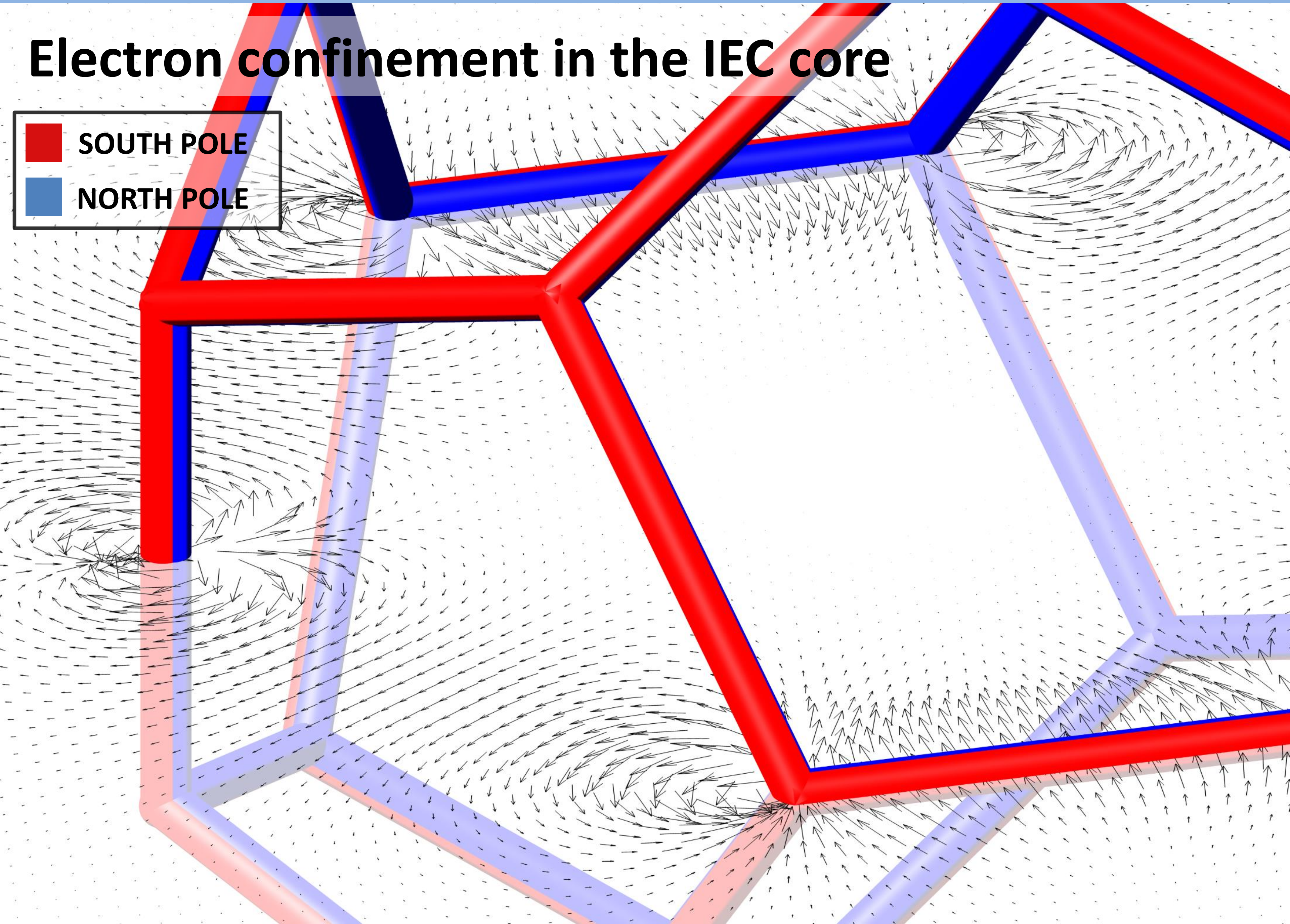


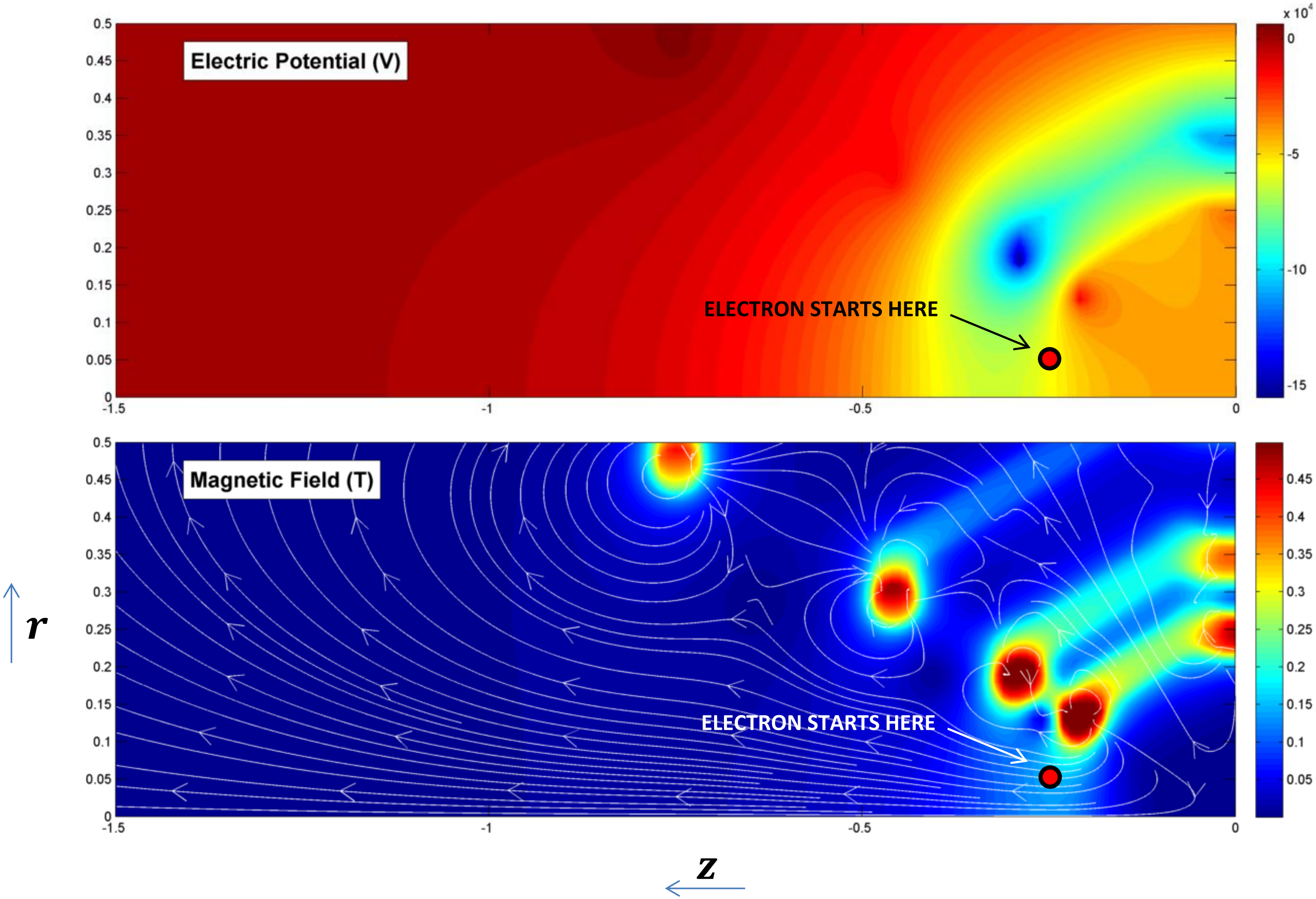
Electron confinement in the IEC core



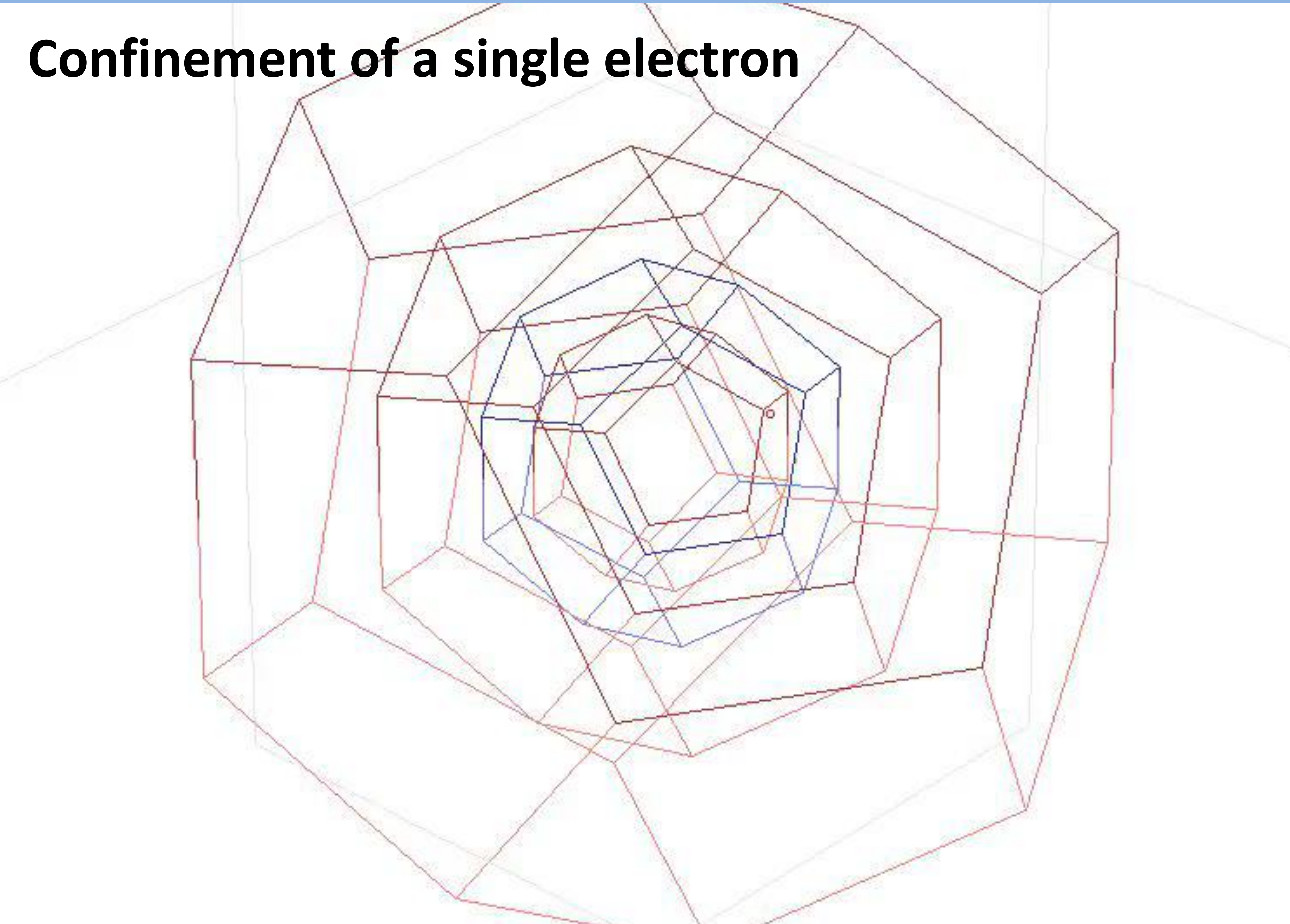
Electron confinement in the IEC core



Approximate E&M fields along a beampath

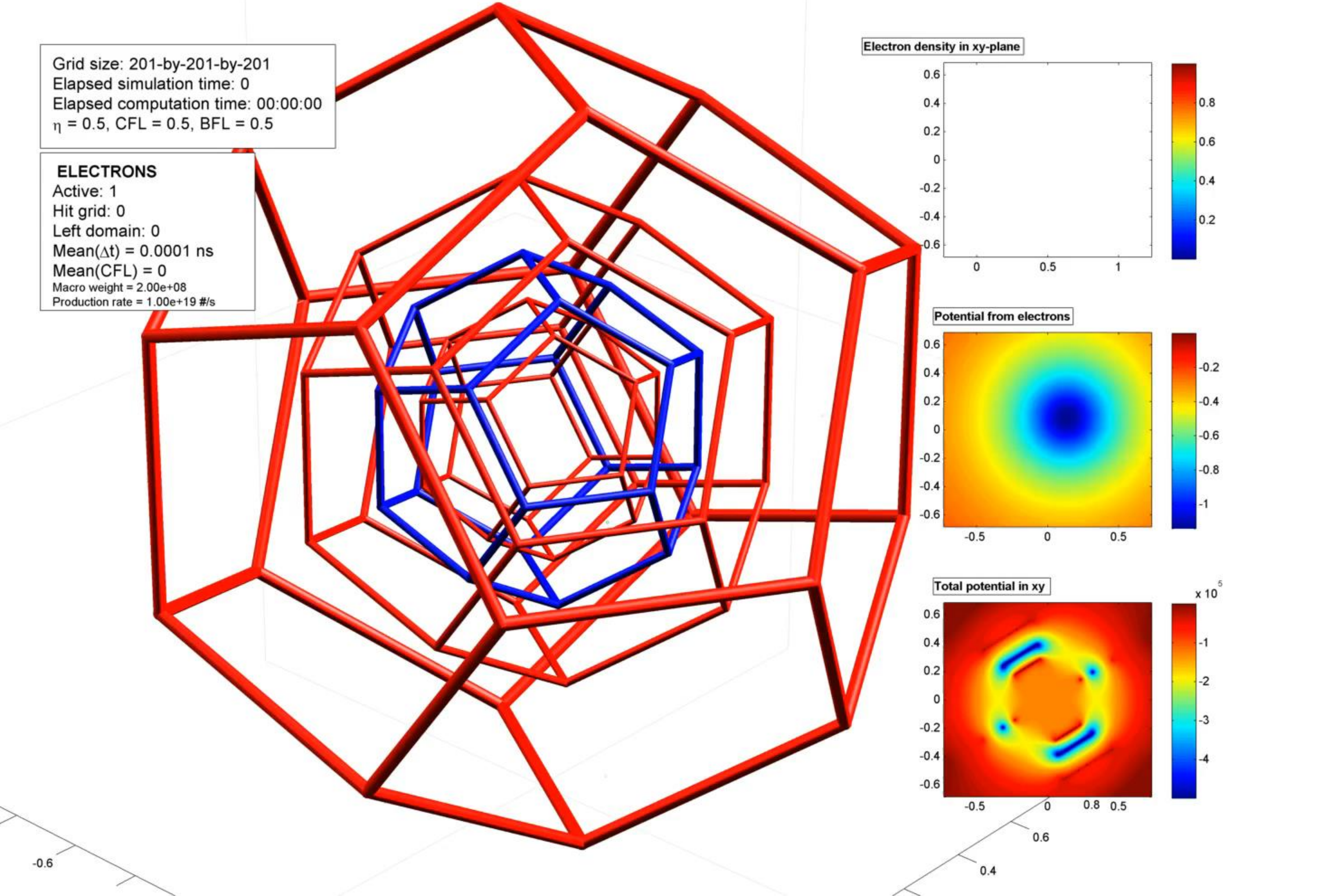


Confinement of a single electron



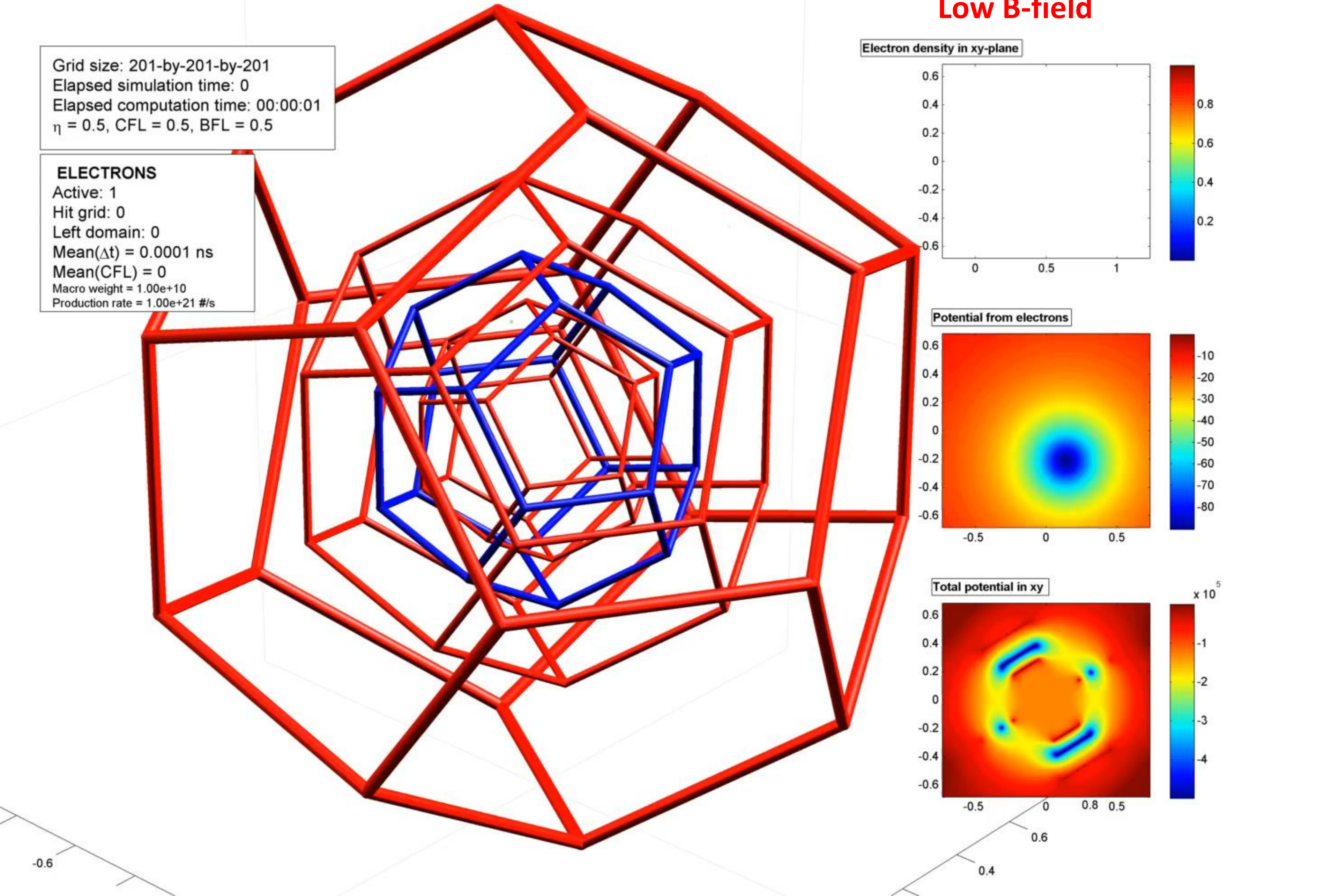
Electron Confinement

Low Density / Low B-field



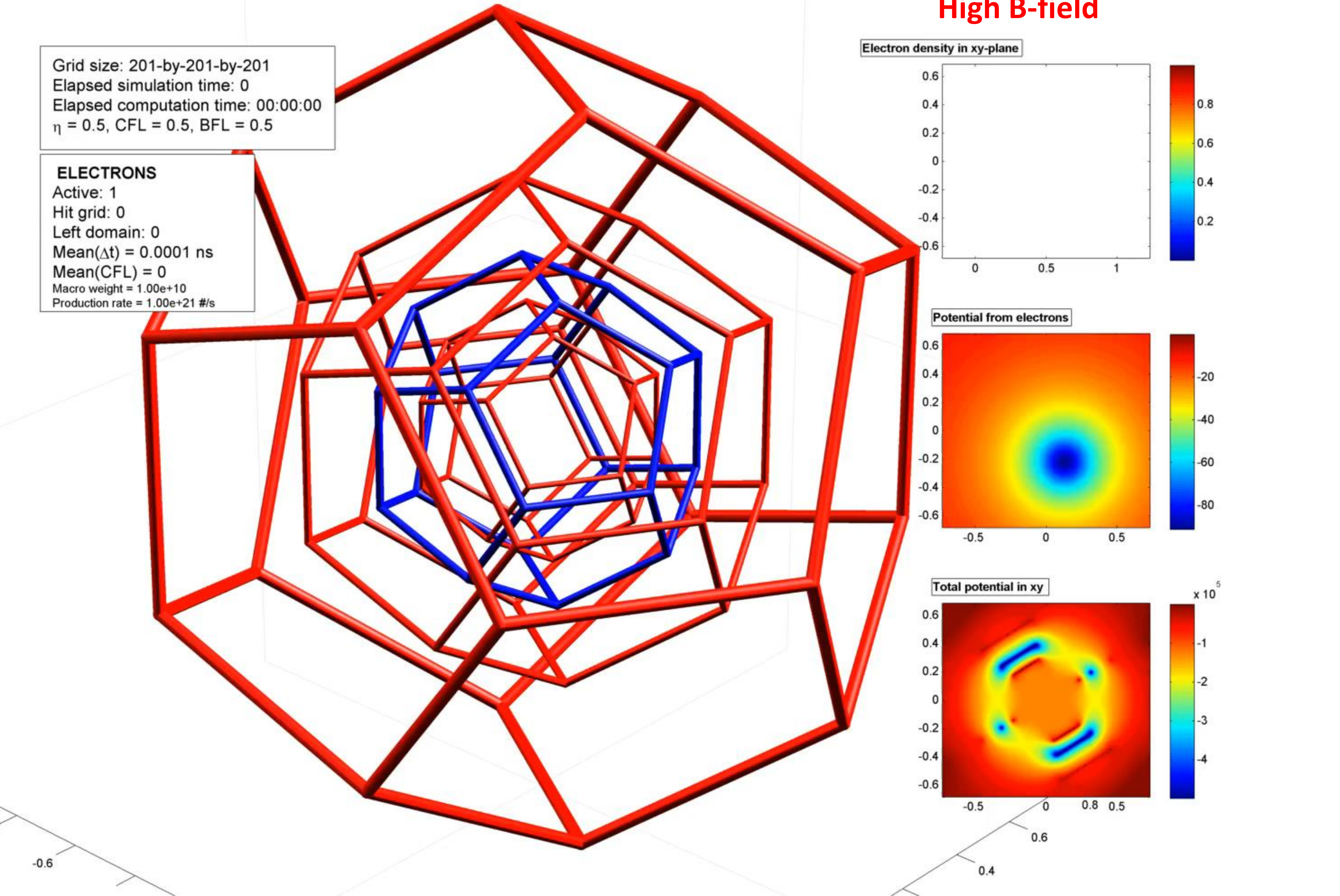
Electron Confinement

High Density
Low B-field



Electron Confinement

High Density
High B-field



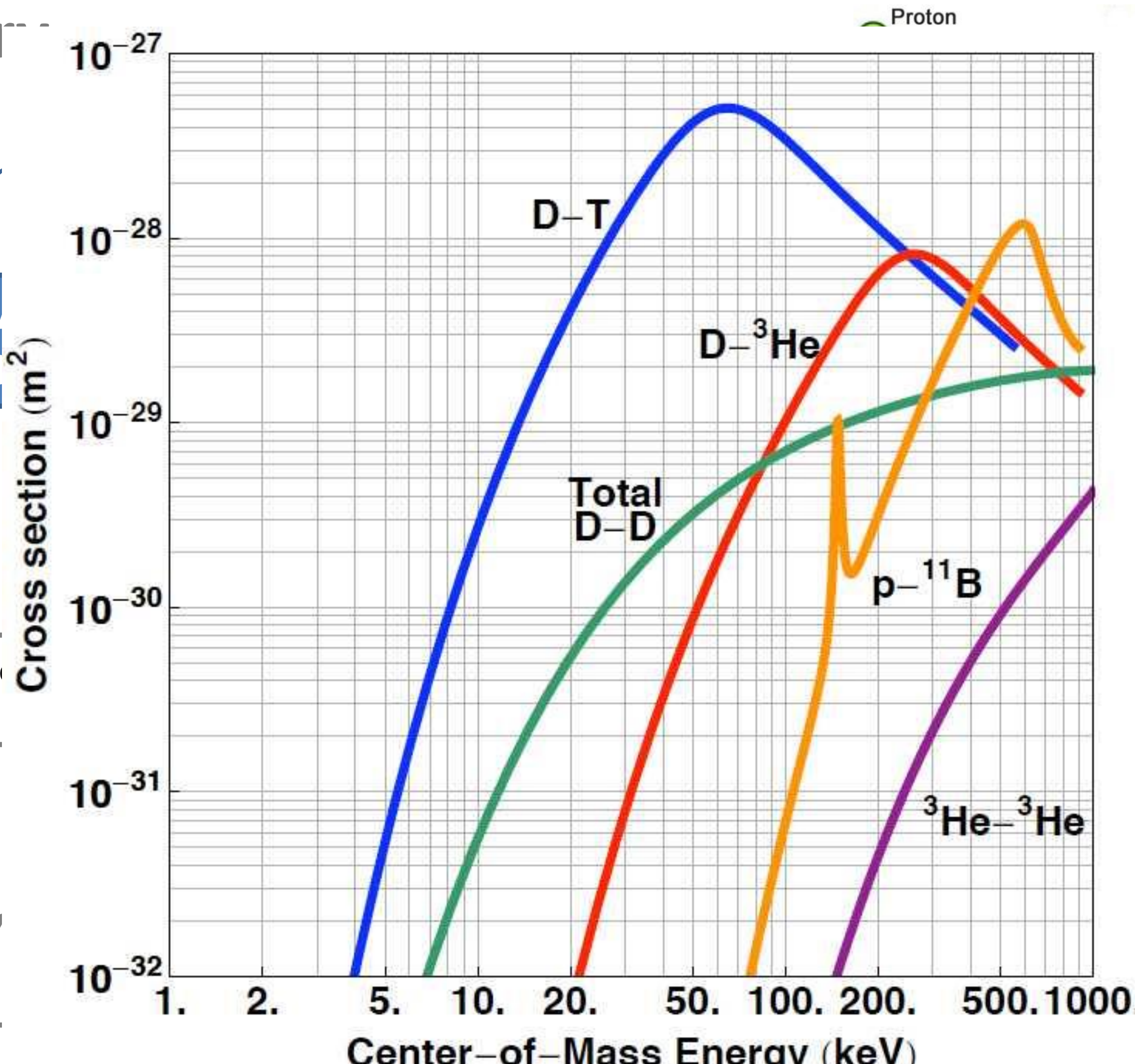
Summar

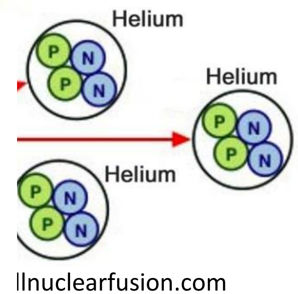
Pathway to r

ION BEA
FOCUSI

Reduce i
grid collis

THERMALIZATION





p-^{11}B fuel

REDUCE
BREHMSSTRAHLUNG LOSSES

DIRECT ENERGY CONVERSION

Advantages and disadvantages of the particle-particle method

ADVANTAGES

External fields calculated only once at simulation start

Little penalty for working in 3-D with large domains

Ideal for large variations in density and velocity scales across the domain

DISADVANTAGES

Computation time scales as N^2

Only suitable (at this point) for modeling one species at a time (ions or electrons) for short timescales

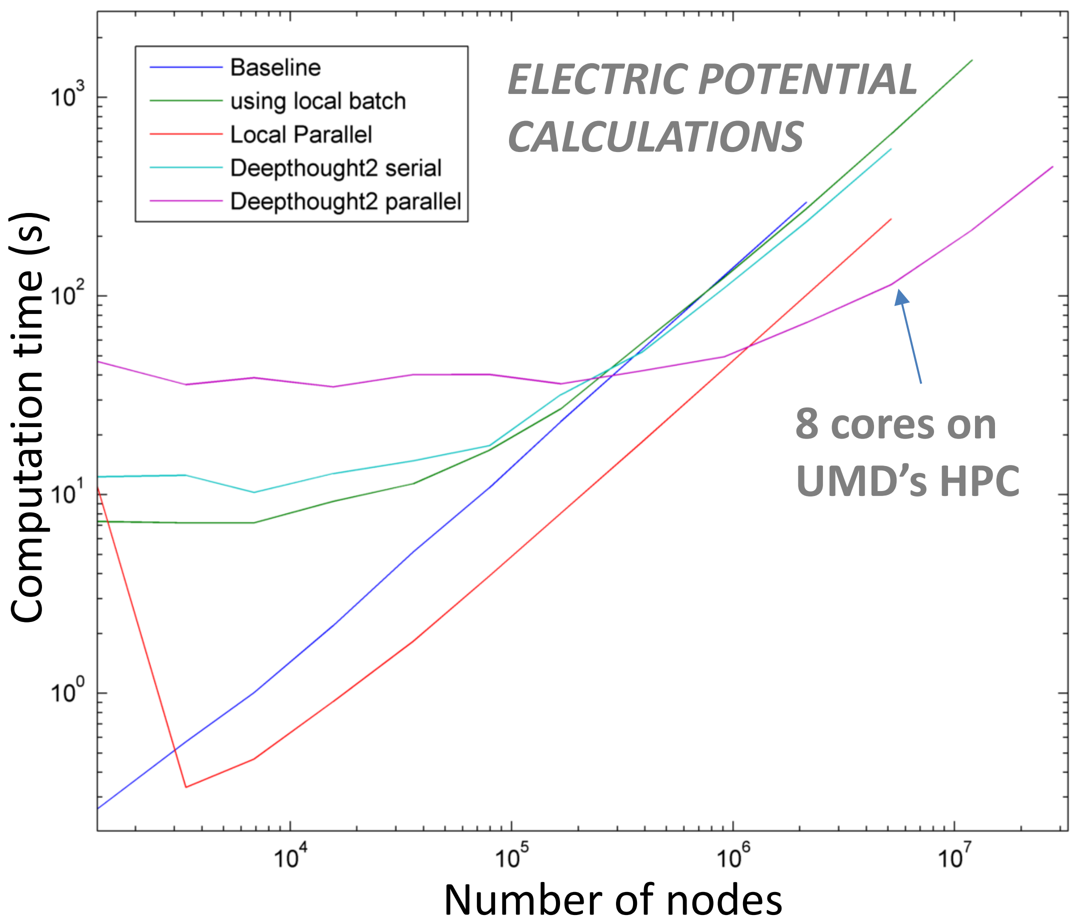
Difficult to simulate to long timescales (thermalization and ion bunching timescales)

Future Work

PROBLEM SIMPLIFICATION

Fast Multipole Method (FMM)

- Simplify from $O(N^2)$ to $O(N \log N)$



HARDWARE

High Performance Computing – UMD's **Deepthought2** cluster

- Run multiple jobs in series (parameter sweep)

  and/or

- Parallelize code for faster execution

The End

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